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Sudipta Chakraborty

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Co-authors: Dr. Arnab Sarma, HOD (Civil), The Assam RGU, Guwahati

Dr.A.R.Kambekar , Deptt.Of CE, SPCE, University Of Mumbai

1	Chakraborty S, Kambekar A. R., Sarma A,	Understanding 'Glacial Geo-engineering': An Innovative Approach for Retarding the Sea Level Rise	Journal of Offshore Structure and Technology, ISSN: 2349-8986 Volume 8, Issue 1, 2021	April 30, 2021,
2	Chakraborty S, Kambekar A. R., Sarma A,	Climate Change And Sea Level Rise In The Last Decade, From The Perspective of Goals Set In The Paris Agreement-An Appraisal	International Journal of Research in Engineering and Technology (IMPACT: IJREAT) ISSN (P): 2347–4599; ISSN (E): 2321–8843 Vol. 9, Issue 6, pp 1–12	Jun 2021,
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Understanding 'Glacial Geoengineering': An Innovative Approach for Retarding the Sea Level Rise

Chakraborty Sudipta[1], Kambekar A.R.[2], Sarma Arnab[3,*]

Abstract

Climate Science is one of the most complex science, which involves physics, fluid mechanics, heat transfer, geology, ocean hydraulics, remote sensing, solar radiation, and many other unknown factors. Human greed has been identified as the principal cause of anthropogenic global warming. Human habitation all over the globe, more particularly in the coastal places are going to face catastrophe due to uncontrolled ever-increasing Sea-Level Rise. Although there have been lot of efforts to control the rise of temperature however the desired result is difficult to be obtained. In spite of thorough and continuous research in the related field lot of uncertainties in finding the best practice is yet to be ascertained. In this paper the authors highlight a new innovative approach i.e., Glacier Geoengineering and apprises the possible effectiveness of the proposed methodology and the merits and demerits have been discussed.

Keywords: Global warming, melting of ice, sea level rise, uncertainties, geoengineering

INTRODUCTION

Climate science and the resultant sea level rise is now a burning topic in terms of danger and threat around the world. As a matter of fact, that from the point of view of climate appraisal, as per UNEP report 2020, till now the year 2020 is on track to be one of the warmest on record, with wildfires, droughts, storms, and glacier melt intensifying [1]. It all happened because of Global warming which occurs when carbon dioxide (CO_2) and other air pollutants collect in the atmosphere and absorb sunlight and solar radiation. Our planet gets hotter as the heat gets trapped within the pollutants which last in the atmosphere up to centuries for years and the radiation of heat cannot escape into space. That's what's known as the Greenhouse effect. After first lustrum of Paris Agreement UNEP report 2020 recorded that the world is still moving towards a temperature rise in excess of 3°C this century. So, sea level rise is unavoidable and inevitable. It's a slow Tsunami and the largest threat [1].

***Author for Correspondence**
Sarma Arnab
E-mail: arnab.sarma@rgi.edu.in

[1]Research Scholar, Department of Civil Engineering, The Assam Royal Global University, Guwahati. Assam, India
[2]Associate Professor, Department of Civil Engineering, Sardar Patel College of Engineering, Mumbai University, Andheri (W), Mumbai, Maharashtra, India
[3]Professor and Head, Department of Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India

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LITERATURE REVIEW

The onus of responsibility for climate warming lies with the human greed. Due to burning fossil fuels, cutting down rainforests and farming livestock humans have immensely influenced the climate change. It is established by scientists that greenhouse effect and global warming is anthropogenic, which contributes to the threatening sea level rise, which will be the biggest catastrophe in the post Covid era. Sea level rises in two ways as an effect from Global Warming. The volume of the ocean is expanding as the water warms. Second, glaciers are melting worldwide. The heating of Earth's surface, oceans as well as atmosphere arises primarily from

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burning of fossils which contributes carbon dioxide, methane, and other greenhouse gases. As per satellite altimeter data Greenland losing mass at a rate of 283 gigatonnes per year and Antarctica at 145 gigatonnes per year, respectively. A gigatonne means one billion metric tons of water which is enough to fill 400,000 Olympic size swimming pools. By now, around 5,000 gigatons of ice has melted, which has already raised the sea les around the word [2].

Nobody is sure whether all the ice sheets will melt over subsequent century. However even small melting can have serious global repercussions. In addition to rising of sea levels, meltwater would hamper the world's ocean circulation. Scientists estimated that in the event of the complete Greenland ice sheet gets melt and the entire meltwater flows into the oceans, it would raise the sea level close to seven meters (23 feet) and the Earth's rotation would be slower by about two milliseconds [3].

DISCUSSION

Scientists forecast that 200 million people in the world would live below the sea level line by 2100. Out of the 200 million directly affected by rising sea levels, researchers estimate that 70 percent will be from eight countries in Asia viz. Japan, Thailand, Philippines, Bangladesh, Vietnam, India, Vietnam, Indonesia. The Intergovernmental Panel on Climate Change (IPCC) has already announced that by 2100 there will be global mean sea level rise in the tune of 1 meter plus. The upcoming Assessment Report 6 of IPCC expected to come out by 2022 will let us know the situation clearly. Reducing sea level rise as much as possible is a difficult task as greenhouse gas emissions varies from country to country depending on use of fossil fuel, the flux of industrial effluents and economic policy [4].

It's true Renewable Energy, Electric Cars, Solar Battery Cars are becoming popular, but all of a sudden, all productions for conventional power from fossil fuel and other sources of Greenhouse gases are not feasible to be discontinued from economic policy point of view. Countries need to set targets for zero deforestation and need to mitigate emissions to limit global warming. It is a gradual process. Earlier Sea Level Rise was understood to be an effect of Global Warming only. Later the scenario of acceleration of melting office in recent years brought lot of changes in the researchers' thoughts. There are evidences that scientific concepts varied within different school of thoughts, there are couple of uncertainties on what is going to happen and how much is going to happen. Sea level Rise will not be same all over the coasts. There will be variation in regional sea level rise due to changes in climate models from Global Climate Model to Regional Climate Model. All these are very complicated process as correct assessment is often difficult for lack of sufficient oceanic data and the scientific assumptions and hypothesizes are very cumbersome. Satellite altimeter data are more reliable than other local measurements and dedicated satellite like Sentinel 6 is on the job. UN body IPCC's forecasts could not be always realistic, rather found more than the projected one. Even there are concepts that even if all emissions are stopped right now, even then the ice shelves will continue to melt for centuries and nothing can be done to restrict and reduce sea level rise. In different countries planning to combat or adapt the situation has already started for quite a few decades. During the climate change conference on December 12, 2015 the Paris Agreement (attended by 196 parties) was an international treaty on climate change aiming to limit global warming preferably to 1.5 degrees Celsius. The first 5-year cycle after this agreement is over and now while entering into the new decade, it's time to evaluate the decided obligations of the participating governments through their "nationally determined contributions" (NDCs) [5].

One recently developed new innovative concept 'Glacial Geoengineering' proposes to hinder melting of the ice and reduce contact of warm water with ice. The term 'geoengineering', a

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mixture of geology and engineering is a large-scale intervention. The perceptions in Geotechnical Engineering like shear stress, buttressing etc. has been analogically applied on ice, snow, permafrost coupled with concept of cooling by cloud. Geoengineering is completely new, of course a wild thought, but not a science fiction in terms of Civil Engineering. Broadly Geo-engineering can be divided into two categories: solar geoengineering i.e., reflecting more sunlight back to space and removal of carbon dioxide aiming to reduce its atmospheric content. The solar geoengineering aims to counter the global action of warming by reflecting radiation to space. In principle, it requires the reduction of a small fraction of incoming sunlight to the Earth to counterpoise the greenhouse gas-induced warming. Concepts to capture and subsequently confiscate carbon through the addition of aerosols like sulphur dioxide to the atmosphere or increase in the reflectivity of clouds has already been into effect. Adding aerosols to the atmosphere to reflect more sunlight might slow the loss of glaciers but will not stop it. Factors like the particle size and life cycle of aerosol, injection strategies for spatial and temporal aerosol, and the chemical interactions with ozone are important for proper use of aerosol in the stratosphere. Also confining the floating area by walls have been thought, which can avoid contact of ice with warm water. Other proposals to reverse the Earth's rising temperatures as an alternative to GHG mitigation also exist. Glacier geoengineering aims at changing the seafloor geometry near glaciers which flow into ocean forming an iceshelf which prevents further melting.

The carbon dioxide removal (CDR) approach aims at sequestering in the carbon geological reservoirs, terrestrial biosphere and in the ocean by removing excess CO_2 from the atmosphere which is the root problem of global warming. The idea of marine cloud whitening is to deliberately increase the cloud droplet number by introducing fine particles near the base of low clouds, thereby making the cloud reflect more sunlight. The Earth can be intentionally cooled by reflecting more sunlight back to space by increase in the surface albedo. In practice, a fine seawater mist can be sprayed from conventional ocean-going vessels or aircraft /unmanned sea craft into the remote marine atmospheric boundary layer. Glaciers that extend from land into the ocean are exposed to both warming air and water temperatures. In addition to the melting that occurs from the air above, warm sea water melts the glaciers from below, causing them to melt faster. Here the walls built on the ocean-floor comes into play. Once in place, the purpose of these barriers would be to block warm water to reduce the melting rate, and to reground the ice as it thickens. The walls would prevent warm water from moving further inland and reduce melting rates there, taking the advantage that the glaciers are already floating. The concept first surfaced in Atlantic magazine (2018) conceptualized by Michael Wolovick, at Princeton University. The uniqueness of his geoengineering proposal is that it does not focus on decreasing greenhouse gases (GHG), the root cause of climate change. It focusses on a consequence of climate change, in this case sea-level rise, as a result of glacial collapse. Would these walls work in reality? Wolovick's computer modelling show that glaciers will be stabilizing after walls are put in place, with some glaciers actually gaining in mass. This possible stabilization would buy some time to retard disastrous collapse of ice sheet [6].

Wolovick's concept envisage an unprecedented scale of engineering project by construction of large underwater walls, composed of an inner layer like sand and an outer layer of boulders. These walls would be strategically built at glacier's edge meeting the ocean. There is also a plethora of engineering matters that need to be addressed. It is important that the foundations for the walls would need to be well protected. This protection could be additional sills built in front of or at an angle to the main sill to redirect currents that could compromise its effectiveness which can take the form of boulders and concrete elements. The seafloor could be quite unstable and soft at places so that placing additional fill for a sill may be potentially difficult and unstable. Wolovick views that it may be necessary to build the wall underneath floating ice shelves, or in the vicinity of dense iceberg mélange. The plan requires the construction of sills by large flat piles of material that sit on the seafloor and of course there are multiple challenges in such mega-engineering project. Something

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like an outer layer of boulders against tides or may be a big pile of sand. Huge size sand-filled Geotubes can also be there. Simply constructing these large walls in front of the world's most unstable glaciers might stop them from collapsing. It seems counterintuitive. Wolovick's sills wouldn't rise above the ocean surface. They wouldn't be sea walls or levees, like those meant to keep water hemmed into one place. The underwater topography of the ocean floor will change [7].

CONCLUSION

Using glacier geoengineering could be a viable option to arrest the flood at the source. Various Surface albedo-based method have already been proposed to increase the albedo of the Earth's surface. Road surfaces in urban areas and roof tops can be painted white to increase the reflectivity. Under the surface of the ocean microbubbles can be created to increase the ocean's reflectivity. However, there are many technical and environmental questions remains unanswered. The processes remain poorly understood how cloud droplet formation and the coupling between salt droplets and clouds happen. Another is hydrofracturing, when ice shelves vanish, the landed glaciers behind them quicken their march to the sea. As air temperatures get hotter, pools of water could form on the floating ice shelves. These pools could quickly disintegrate the ice beneath them. A number of other features suggest pools of meltwater don't always force ice shelves to disintegrate. The results from computer models are worrying. Not every glaciologist agrees that the computer models get these mechanisms right till now. Let's keep an eye how this challenge will be overcome, not sure whether within our life time or not? But human is such a race, we conquered many things in the history and let's be hopeful.

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CLIMATE CHANGE AND SEA LEVEL RISE IN THE LAST DECADE, FROM THE PERSPECTIVE OF GOALS SET IN THE PARIS AGREEMENT-AN APPRAISAL

Chakraborty Sudipta[1], A. R. Kambekar[2] & Sarma Arnab[3]

[1]Research Scholar, Department of Civil Engineering, Assam Royal Global University, Guwahati. Assam, India

[2]Associate Professor, Department of Civil Engineering, SPCE, Mumbai, India

[3]Research Scholar, Head of Department of Civil Engineering, Assam Royal Global University, Guwahati, Assam, India

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ABSTRACT

In the United Nations Framework Convention on Climate Change (UNFCCC), during the conference of 196 parties on 12 December 2015, the Paris Agreement was an international treaty on climate change aiming to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. It was for the first time a binding agreement took place bringing all nations into a common cause towards undertaking ambitious efforts to combat climate change. The parties agreed to adopt economic and social transformation, based on the best available state of the art of science to strategize the adaptability to unavoidable imminent changes. The first 5-year cycle of increasingly ambitious climate action carried out by countries is now over and at the end of 2020, while entering into the new decade, it's time to evaluate the effect based on the decided obligations of the participating national governments – the most important being the development and implementation of their" nationally determined contributions" (NDCs). Scientific research, being a continuous process there has been evaluation in the theories related to climate models and the speculations had been undergoing changes. Although the melting of large quantity of ice was not fully unexpected but the acceleration of melting in the last lustrum and the expected huge volume of melt water has led the scientific community to believe that the speculations on the resultant effects of warming could vary to a large extent. The agreement was entered into force on 4 November 2016 and meanwhile there has been continuation of accelerated increase in melting of ice shelves in Greenland and Antarctica. Besides, almost simultaneously in the decade from 2010-20, a number of anomalies in IPCC projections, observations on uncertainties and advent of CMIP5 to CMIP6 have also been documented in literature. Based on these facts by researching in different randomly chosen publications vis-à-vis current observations of United Nation Environment Programme Report 2020 and Climate-Transparency-Report-2020, this paper retrospectively inspects the past findings. The paper attempts to evaluate the present situation and assess how much has been achieved as per Paris agreement. While evaluating the achieved goals, the recent approaches on effect of orography, glacier geo engineering and ansatz approach have been examined this may usher out a clue towards newer direction of research.

KEYWORDS: *Climate Change, Global Warming*

INTRODUCTION

Way back in 2007, vulnerabilities of three global coastal cities to climate hazards viz. Mumbai, Riode Janeiro and Shanghai was identified by AlexDe Sherbininetal. In terms of three elements: system exposure etocrises, stresses and shocks; inadequate system capacity to cope; and consequences and attendant risks of slow (or poor) systemrecovery by developing a vulnerability framework. They addressed the then and future vulnerability to climatehazards using standard sets of climate change and sea-level rise in a sustainable path (reduced emissions) and business as usual (increased emissions) scenarios. Projections of sea-level rise due to melting land-based glaciers and polar icecaps was stated to range from 0.2 to 0.9 metres by 2100 highlighting the apprehension that estimates could be superseded duet orapid melting in Greenland and Antarctica. They adopted a common projected sea-level rise of 50 centi metres by 2050, although local variations in land subsidence was believed to affect the relative sea-level rise in each location[1].

In 2008 it was found that total impact of climate change on economy of the city of Mumbai, even when conservatively estimated would be enormous. Rakesh Kumaretal. Computed the economic impact to infrastructure at Mumbai city getting affected in the region near the shore. They assumed that sea water will penetrate 200 min land and because of rise in the sea level and ingress of sea water infrastructure along the coast line and inside the shore will get affected [2].

Rajawat AS et al. noted in 2010 that IPCC, 2007 has predicted that the global sea level will rise by about 18 to 59cm by the 2100, whereas newer models suggested that the sea level rise because of melting of glaciers, vanishingof ice sheets could by the end of this century be 1.5 m. They mentioned about contemporary evidences of large-scale ice melt in the three major icere positories of the world– the Arctic, the Greenland and the Ant arctic regions and proclaimed that there is a further possibility of increase of as much as five meters, in the event of the collapseof the Greenland and West Antarctic ice sheets. It was stressed upon that the impact of the rising sea levels would be variable depending upon the characteristics of the coast such as geomorphology and slope and waves andtidesat coastal periphery. A CVI (Coastal Vulnerability Index) was prepared by the authors.

They integrated theweighted rank values of the five different variables using a formula viz.:

$CVI = 4g + 4s + 2c + t + w$,

where g wascoastal geomorphology,

s was coastal slope,

c was shoreline change history,

t was mean spring tide range and

w being significant wave height.

Keeping in view of their relative significance in influencing the coastal response tosea-levelrisethenumbers 2and 4 indicated the relative weight age of different variables [3].

Stefan Rahmstorf in 2012 noted the variations in projections of global sea-level riseby different authorities. The projections upto 2100 speculated by IPCC report 2007, Delta Commission of the Dutch government 2009,Scientific Committee on Antarctic Research 2009, Arctic Monitoring and Assessment Programme 2011 and US Army Corps of Engineers were1m,1.1m,1.4m,1.6 mand1.5m respectively. These pessimistic views are perhaps due to the fact that sea level has been rising at least 50 % faster in the past decades than projected by the IPCCandtherateofriseoverthepast20years has accelerated to around 3mm yr^{-1}i.e.,about threefold from around 1mm yr^{-1} at the start of the 20th century. The observed net mass loss of the two big continental ice sheets raisesdoubt on the assumption that ice accumulation in Antarctica would largely balance ice loss from Greenland in the course of further global warming. Hence the IPCC projections, which almost did not consider any further acceleration in the 20th century, loses its merit to be plausible. The foregoing facts speak about inconsistent and varying results [4].

Williams Jeffress S acknowledged in 2013 about the strong consensus among climate scientists that sea level isvery likely to rise at accelerated rates for the rest of the 21st century and for centuries beyond. Also, concurrently it was agreed that the evidence for Global Sea Level Rise due to climate warming is debated. It was pointed outthat IPCC 2007 projections did not include the potential for melting of major land-based ice sheets on Greenlandor West Antarctica due to a lack of understanding of ice sheet dynamics at that time. A very large amount of potential sea-level rise from melting of this ice sheets but could not be modeled with high confidence and revision in IPCC's next report was expected. It was stated that the gravitational effects and shifts in ocean circulationpatterns are likely to result in a nonuniform rise in sea level. The topic sea level rise was viewed as a subject ofdebate in the literature. Questions remained whether Global Sea Level will be as predicted from semi empirical models and can be linked to observed global warming? And is it a global acceleration, a region-specific acceleration due to warming, the product of a multi decadal variation, or some combination of these [5]?

BhoreS.J., opined about‘ Paris Agreement on Climate Change’ in 2016 as a Booster to Enable Sustainable Global Development and Beyond; reiterating its main objective to decrease greenhouse gas emissions significantly as soon as possible, keeping the increase in global average temperature to well below 2^0C, and to1.5^0C if possible. Increased greenhouse gas emissions and the rise in global temperature had been damaging global climate, biodiversity, and ecosystems. It is also adversely affecting the global food supply chain, global public health, and global advancement as a whole. If all these are considered the green house gas emissions and the resultant rise in global temperature will affect the atmosphere, the biosphere, the lithosphere, and the hydrosphere. It was considered extremely necessary for the global community to come together and act together to combat with the challenges posed by climate change. The predicted data suggest that global average temperature could increase by 4.8^0C by the end of 2100, whereas the intended threshold is 2^0C (Figure 1). To make this planet a sustainable healthier and happier place to live, PACC is regarded to be very bold and ambitious step taken by the UN to achieve the SDGs (sustainable development goals) globally [6].

Paris Agreement called for achieving the SDGs (Sustainable Development Goals) based on implementation of NDCs (Nationally Determined Contributions) by respective nations. However, finding it difficult for Govt. alone to combat the situation, Schaer, C. et al. in 2018 mooted the idea of promoting private sector engagement in climate change adaptation and flood resilience in their case study undertaken at Mumbai. The authors presented a framework developed for MSMEs (Micro Small and Medium Enterprises) to make informed risk reduction and adaptation decisions to implement effective measures to minimize the recurring adverse impacts of climate related disaster like floods on their business operations. 100 nos. of MSME units were served detailed questionnaires which focused on recurrent floods, associated damage costs and available response measures. The authors established the need to encourage private sector participation in adaptation efforts. Also, in the case of smaller actors such as MSMEs they insisted for a policy push from the government in the form of incentives to new industrial estates. Inclusion of flood resilience in building codes as a key element in support of the adoption of resilience building measures by private sector players was also suggested [7].

In 2019 it was noted by Kulp et al. that in the case of early-onset of Antarctic ice sheet instability, under higher emissions scenarios, the twentyfirst century sea level rise may approach or in the extremes exceed 2 m. Such a rise obviously can create havoc devastating flood and they opined that in order to undertake proper efficient coastal planning translating sea-level projections into potential exposure of population is of paramount importance and critical to determine benefits to people during climate mitigation, as well as to evaluate the costs of failure to act. According to them, the estimated quantity of global mean sea-level rise (i.e., below 2m) is comparable to the positive vertical bias in elevation data in the principle digital elevation model (DEM), derived from NASA's Shuttle Radar Topography Mission (SRTM), used to assess global and national population level exposure to projected sea or coastal flooding is most commonly expressed as total exposures to extreme coastal water levels. Population Exposure (the total estimated exposure below a particular water level), but is increasingly also presented as marginal exposure (the difference in exposure above a contemporary baseline). End century projections ranged from 50–70 cm under representative concentration pathway (RCP) 4.5 and 70–100 cm under RCP 8.5. Two representative sea- level projections K14 & K17 were considered. K14 is a probabilistic projection and K17 although not probabilistic emphasizes the possibility of more rapid sea-level rise because of unstable ice-sheet dynamics. It was observed that 190 M people (150–250 M, 90% credible intervals) currently occupy global land below projected high tide lines for 2100 under low carbon emissions These figures in fact is triple from the SRTM-based estimates of 28 M and 65 M. Irrespective of emissions scenario or sea-level model, it was found that more than 70% of the total number of people worldwide currently living on implicated land are in eight Asian countries. These countries are China, Bangladesh, India, Vietnam, Indonesia, Thailand, the Philippines, and Japan [8].

L. C. HAHN et al. stressed upon the Importance of Orography for Greenland Cloud and Melt Response to Atmospheric Blocking in 2019. They reanalyzed the satellite data in addition to a regional climate model with a focus on the previously neglected role of topography. During recent extreme blocking summers, it was found that that anticyclonic circulation anomalies over Greenland produce cloud changes are dependent on orographiclift and descent. The resulting increased cloud cover over northern Greenland was found to promote surface longwave warming, while reduced cloud cover in southern and marginal Greenland favours surface shortwave warming. It revealed that orographic effects were responsible to produce area-averaged decreasing cloud cover. Incidentally the extreme melt was observed in the summer of 2012. The melt response to large-scale circulation variability was partially dependent on the Greenland topography. These results suggest that future melt will depend on the pattern of circulation anomalies as well as the shape of the Greenland Ice Sheet [9].

Marco Tedesco et al. observed in April 2020 that understanding the role of atmospheric circulation anomalies on the surface mass balance of the Greenland ice sheet (GrI S) is fundamental for understanding contributions to sea level rise. A combination of all the factors like reanalysis data, remote sensing observations, regional climate model outputs, and artificial neural networks was considered. It was found that those unprecedented atmospheric conditions occurred in the summer of 2019 over Greenland. These generated new records of surface mass balance (SMB), runoff, and snowfall. The anticyclonic conditions were also responsible for reduced cloudiness in the south and consequent below-average summer snowfall and albedo in this area [10].

Recently in International Conference on Oceanography for West Asia held at Tehran, Iran in September 2020 Ahammed Basheer K. K. expressed their concern on the anthropogenic activities raising conflict in bio rich marine ecosystem in the eastern coast of India. They highlighted the sensitivity of coastlines to sea-level rise and commented about higher impact of the increasing trend of cyclones and associated storms, increases in precipitation, and changes in the ocean temperatures. They mentioned about availability of varieties of tools and techniques for studying climate vulnerability. The vulnerable locations were identified using a digital elevation model with extreme surge height, sea level rise rate, historical cyclone events, and intensity. They observed that around 8000Km^2 areas in the states viz. West Bengal, Odisha, and Andhra Pradesh are vulnerable and susceptible to storm surges, whereas Tamil Nadu and Puducherry are least sensitive regions on the eastern coast of India. It was revealed that the use of the geospatial application is the most reliable and coast effective approach for disaster preparedness and management. They also advised that for addressing the additional stress of climate change may require new approaches to managing land, water, waste, and ecosystems [11].

Hofer Stefan et al. observed in 2020 that for a similar extreme surface warming of 8.5 W/m^2 in 2100, between the high-emission scenario from CMIP5 (RCP8.5) and CMIP6 (SSP58.5) Greenland Ice Sheet surface melting will almost double in the twenty-first century. It is stated that future mass loss rate of Greenland Ice Sheet strongly depends on the future global temperature rise and therefore anthropogenic greenhouse gas emission rates and also on the strength of melt-albedo feedback. The Global climate models (GCMs) of the Climate Model Inter- comparison Project 5th Phase (CMIP5) show a clear signal of above average temperature rise in various different emission scenarios. However, due to imperfect cloud microphysics and missing recent Greenland circulation anomalies, the absolute magnitude is still subject to uncertainties, mainly. The latest CMIP 6th Phase (CMIP6) incorporates more complex model physics, a higher spatio-temporal resolution, and a more realistic coupling between the different Earth system components and better constrained emissions of aerosols and other near-term climate forcers. [12]

Shane Elipot very recently in October 2020 commented that modern global mean sea level (GMSL) rise is an intrinsic measure of anthropogenic climate change which is triggered by thermal expansion of the warming ocean's water and the melting of terrestrial ice. He showed that an array of surface drifting buoys tracked by a Global Navigation Satellite System (GNSS), could provide estimates of global mean sea level (GMSL) and its changes. It was demonstrated that with an uncertainty less than 0.3 mm yr−1 could be achieved with GNSS and such measurements could ultimately provide an independent and resilient observational system. This was opined to be a better option in comparison to the ongoing tide gauge and satellites records [13].

Elhacham, E. et al. for the first time in history commented in 2020 that humanity has become a dominant force in shaping the face of Earth. They quantified the ‘anthropogenic mass’ i.e., human-made mass and linked itwith the overall living biomass on Earth (1.1 teratonnes). It is opined that due to ramped up consumption the weight of natural resources - the living biomass for trees, plants and animals—has halved since the agricultural revolution. For every person on the world, anthropogenic mass adequate to quite his or her bodyweight is produced hebdomadally. Manmade material is likely to weigh about three teratonnes by 2040 at the current growth rate, [14].

Jennifer Huang et al. in the report of Centre for Climate and Energy Solutions,2020 highlighted a broad range of climate actions across many spheres of society inspired by the Paris Agreement. The agreement, according to the report, provided a strong signal to actors beyond national governments, served as both a driver and abenchmark for climate action across society. The Agreement has inspired countless commitments and actions by a wide range of actors across society. The long-term goals that countries built into the agreement to guide national efforts have served at the same time as a driver and benchmark for a growing abundance of bottom-up efforts. In the oil and gas sector, Shell, BP, and Equinor committed in 2020 to net-zero emissions by 2050 at the latest. Volkswagen in transportation sector committed to being carbon neutral by 2050 and announced a decarbonization program to fulfil its commitment to the Paris Agreement. Maersk, the world's largest container ship and supply vessel operator, set a net- zero carbon goal for its operations to contribute to reaching the Paris Agreement's goal of staying well below 2C temperature rise. In the building materials sector, Lafarge Holcim, the world's largest producer of cement, committed in September 2020 to become a net-zero company by 2050 and to join Business Ambition for 1.5°C. In February 2020, CEMEX, a Mexican multinational company and one of the biggest building materials companies worldwide, committed to net-zero emissions across its products and operations by 2050.In the mining sector, Vale, a Brazil multinational mining and logistics company and the world's largest producer of iron ore, pellets, and nickel, committed to carbon neutrality by 2050 to align with the Paris Agreement, a goal referenced throughout its 2019 sustainability report.42 In 2019, BHP, one of the world's largest mining companies, committed to net-zero operational emissions by 2050, and in 2020, the company updated its climate goals aligned with the Paris Agreement[15].

Lockley Et al. recently in 2020, mentioned that the high-end sea level rise (SLR) threat over the next few hundred years comes almost entirely from only a handful of ice streams and large glaciers but acknowledged that literature on ice sheet conservation is limited. The trend of research focuses on blocking warm ocean waters accessing ice shelf cavities and increasing snow fall. The ideas evolved included draining or freezing the seabed, altering albedo, keeping snow intact, create obstacle like buffer, increasing shear strength of ice, limit fracturing of ice, buttressing etc. and also novel ideas like cooling glaciers through cloud by reengineering climate science. They opined that spatially limited interventions at source may provide globally-equitable mitigation from rising seas. It is stated that even if emissions fall to zero after say 2050, the risk of dramatic sea level rise will continue. They outlined new potential interventions summarizing novel and extant geotechnical techniques for glacier restraint on ice sheets with an overview on solar radiation management, seeking to address impacts (like sea-level rise) by controlling global average surface temperature (Figure 2). They expressed their grave concern on the severe unresolved scientific and engineering challenges in this regard and suggested to explore more applying Glacier Geo engineering [16].

Rodehacke, C. B. et al. in 2020 examined how the implementation of an uncertain mathematical framework (ansatz) can be utilized to find sea level contribution in an ensemble of ice sheet simulations by putting the boundary condition of precipitation. They tested a hypothesis that the ansatz of the precipitation determines whether the global sea level rises or falls. They tested two precipitation boundary conditions i.e., vapor and solid for sublimation or solid and liquid for melting, considering: (i) both the ocean and air temperature anomalies and the precipitation anomalies from CMIP5 models and (ii) only the ocean and air temperature anomalies from CMIP5 models and compute the precipitation anomalies scaled by the air temperature anomalies. Clausius-Clapeyron equation pertaining to the relationship between the pressure and temperature for conditions of equilibrium between two phases was taken to resolve the hypothesis. Their ensemble study suggested that some areas glaciers will lose ice in the future [17].

Klaus Wyser et al. observed in 2019 that compared to the values obtained with earlier versions for CMIP5, many modelling groups that contribute to CMIP6 (Coupled Model Inter comparison Project phase 6) have found better Equilibrium Climate Sensitivity (ECS). They investigated the developments which caused the increase in the ECS in EC-Earth model (European community Earth-System Model) since the CMIP5 era. They also affirmed that the ECS increase has an effect on the more advanced treatment of aerosols. The largest contribution coming from the effect of aerosols is found to effect on cloud microphysics (cloud lifetime or second indirect effect). They opined that the obtained results cannot be easily generalized as aerosol-cloud interaction process may vary from CMIP5 to CMIP6, but their results found strong ECS with the details of the aerosol forcing [18].

Zelinka, M. D et al. illustrated the causes of higher climate sensitivity in CMIP6 models in 2020. They observed that in the latest generation of global climate models, the temperature response has increased substantially. Thisaccordingtothemisduetoanabruptquadruplingofatmosphericcarbondioxide, as well as low cloud water content. Enhanced planetary absorption of sunlight itself is an amplifying feedback that ultimately results in more global warming. The enhanced sensitivity relative to the previous generation of models is driven by differences in the physical representation of clouds in models. Both the multimodal mean and intermodal variance in ECS (effective elimate sensitivity) have increased substantially in CMIP6 relative to CMIP5, though only the latter change is statistically significant at 95 % confidence [19].

The Emissions Gap Report 2020 jointly published by United Nations Environment Programme with Technical University, Denmark noted that despite a brief dip in carbon dioxide emissions caused by theCOVID-19 pandemic, in variance with the Paris Agreement goals of limiting global warming to well below 2°C and pursuing 1.5°C, the world is still moving towards a temperature rise in excessof3°Cthiscentury.Tillnowtheyear2020ison

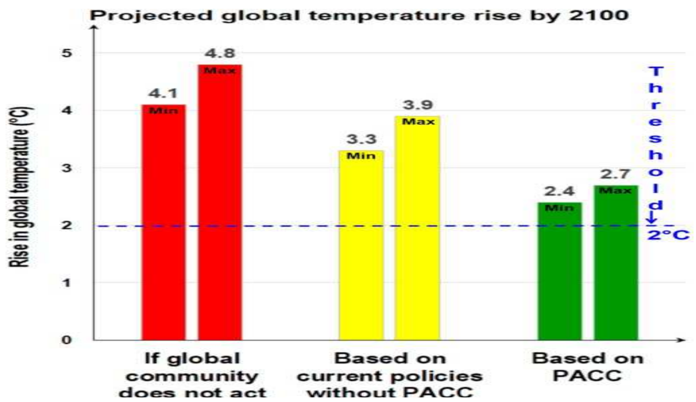

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Figure 1: Projected Global Temperature Rise by 2100 and the Effect of the Paris Agreement on Climate Change.

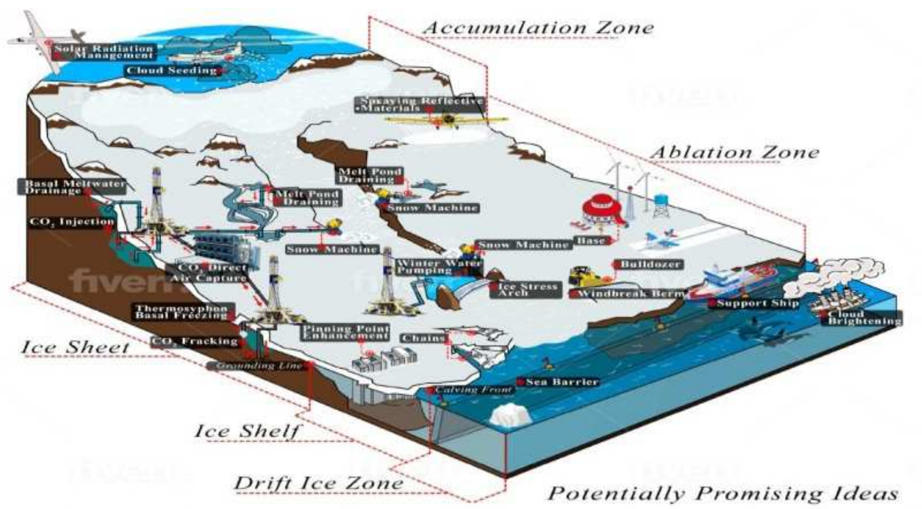

Figure 2: Schematic Re Presentation of Glacier Intervention Engineering Schemes.

(**Note:** In this cartoon the ice area relative to the interventions is about 1 million times smaller than in reality, and it would beun likelyt outilize more than one method on any particular glacier.)

Albe do: reflective materials, draining melt ponds, snow making machines; cloud seeding. **Beddrying & binding:** meltre moval; thermosyphon base freezing; enhanced Oil Recovery analogues; CO2hydrate formation; CO2 fracking-chilling. **Ice shelf but tressing:** enhancing pinning points; thickening / strengthening ice with pumps, snow making machines, thermosyphons and wind breaks; draining shelf melt; tensilere inforcement.

Environmental modification: cloud brightening, under water berms/sheets, manipulating ocean/air currents, regional solar radiation management. Advances in Climate Change Research, 2020, ISSN1674-9278https://doi.org/10.1016/j.accre.2020.11.008

One of the warmest on record, with storms, wild fires, droughts, and in testified glacier melt. If current trends are continued, combined emissions from shipping and aviation internationally will consume between 60 and 220 percent of allowable CO_2 emissions by 2050 under the 1.5°C scenario.

The CO_2 equivalent of total greenhouse gas emissions in 2019 touched a new high of 59.1 gigatonnes. The number of countries who had adopted, announced or were considering net- zero goals counts to 126, whose contribution is 51 per cent of global greenhouse gas emissions. The report acclaims the Biden-Harris climate plan and declared that in the event the US adopts a net-zero target by 2050, this would increase to 63 per cent.The report points out a huge discrepancy between the ambition of the goals and the inadequate level of ambition in NDCs. UNEP report acknowledges that the emissioncountfromtherichestonepercentoftheglobalpopulationismorethantwiceofthatfromthepoorest50percent.This suggest that to reduce their footprint by a factor of at least 30 to stay in line with the Paris Agreement targets. The so called lite needs to be more and more responsive. [20].

CONCLUSIONS

The Climate-Transparency-Report-2020 published that G20 # countries account for90+% of cumulative historical CO_2 emissions and 70% of current emissions, where 77% of GHG emissions (primarily CO_2) are from Energy. There port acknowledged that energy related CO_2 decreased by 0.1%, share of renewable grew to 27 in G20 in 2019, continue to grow in 2020, steep decrease of aviation fuel demand (pandemic contributed) fossil fuels still counted as 81.5% of primary energy for G20Countries. The report advises that G20countries need to set targets to set targets for zero deforestation and need to mitigate emissions to limit global warming.

The Climate Transparency Report-2020 suggests 5 principles of a Green Recovery which can accelerate Climate Actions & bring sustainable co-benefits i.e.

- Investment in sustainable physical infrastructure,
- Invest in Education, Research and Development
- Reinforce Policy, Regulations & incentives for sustainable future
- Invest in Nature Based Solutions & The environment
- Introduce conditionality for greener bailouts.

However, till date as per UNEP 2020 the opening for using recovery measures to accelerate a green transition as promised in Paris Agreement has largely been missed. The Paris Agreement goals will further slip out of reach, lest the situation is reversed. Parties to the Paris Agreement are expected to update NDCs (Nationally Determined Contributions) in 2020. UNEP called the Governments should pull out all the stops to implement a green recovery and strengthen their pledges before the next climate meeting in 2021. Government pledges under the Paris Agreement, i.e., the NDCs are still woefully in adequate. Predicted missions in 2030 leave the planet on the trail to a 3.2°Cincreasethis century, albeit all unconditional NDCs are fully implemented. Although the COVID-19 pandemic caused a dip in 2020 emissions, this will not bring the world closer to the Paris Agreement goal of limiting global warming this century to well below 2° C and pursuing 1.5°C. A significant opportunity for countries to implement low-carbon policies and programmes is available to be executed. Zero-emissions technologies and infrastructure, reducing fossil fuel subsidies, barring fossil fuel plants, promoting nature-based solutions –including large-scale landscape restoration and reforestation to be prioritized. One of the most significant climate policy developments of 2020 is that number of countries committing to net-zero emissions goals by mid- century is increasing. To remain feasible and credible, the commitments of Paris Agreement need to be urgently translated intorealistic action and reflected in NDCs. More countries need to strategize for net- zero emissions goals. The shipping and aviation sector, which contributing to 5 per cent of global emissions requires more attention. Governments and people should be ready to avoid high-carbon consumption, replacing domestic short half lights with rail, enabling cycling and car-sharing, improving energy efficiency of housing, focusing more and more on renewable energy, reducing food waste etc. Private Sector participations to monitor and achieve the goals can be a usable solution and above all individual motivation to rise to the occasion is an absolute necessity.

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Impact of Climate Change on Sea Level Rise along the Coastline of Mumbai City, India

Chakraborty Sudipta, A. R. Kambekar, Sarma Arnab

***Abstract*—**Sea-level rise being one of the most important impacts of anthropogenic induced climate change resulting from global warming and melting of icebergs at Arctic and Antarctic, the investigations done by various researchers both on Indian Coast and elsewhere during the last decade has been reviewed in this paper. The paper aims to ascertain the propensity of consistency of different suggested methods to predict the near-accurate future sea level rise along the coast of Mumbai. Case studies at East Coast, Southern Tip and West and South West coast of India have been reviewed. Coastal Vulnerability Index of several important international places has been compared, which matched with Intergovernmental Panel on Climate Change forecasts. The application of Geographic Information System mapping, use of remote sensing technology, both Multi Spectral Scanner and Thematic Mapping data from Landsat classified through Iterative Self-Organizing Data Analysis Technique for arriving at high, moderate and low Coastal Vulnerability Index at various important coastal cities have been observed. Instead of data driven, hindcast based forecast for Significant Wave Height, additional impact of sea level rise has been suggested. Efficacy and limitations of numerical methods vis-à-vis Artificial Neural Network has been assessed, importance of Root Mean Square error on numerical results is mentioned. Comparing between various computerized methods on forecast results obtained from MIKE 21 has been opined to be more reliable than Delft 3D model.

***Keywords*—**Climate change, coastal vulnerability index, global warming, sea level rise.

I. Introduction

SEA level rise is considered as one of the most important impacts of anthropogenic induced Climate Change and a serious threat to countries (including India) with human settlements and economic activities concentrated in coastal regions. Globally sea level has been rising during 2006–2015 at the rate of 3.6 mm per year which is accelerating in recent years and by 2100, the global mean sea level rise may exceed 1 m [1]. While exploring forthcoming Sea Level Rise at the coast of Mumbai, the authors have reviewed the related literature researched in the last decade (2010-2019) in a chronology aiming at ascertaining the efficacy of methods with various scenarios across the shorelines.

Chakraborty Sudipta is Research Scholar, Department of Civil Engg., The Assam Royal Global University, Guwahati.Assam-781035, India (phone: +919560793289; e-mail: schakrabortydc@rgu.ac).

Kambekar A.R. Dr., is with Department of Civil Engg., Sardar Patel College of Engineering, Mumbai University, Andheri(W), Mumbai-400058, India (phone: +919224306150; fax: +91-22-26237819; e-mail: a_kambekar@spce.ac.in).

Sarma Arnab Dr., is with Department of Civil Engg., The Assam Royal Global University, Guwahati, Assam-781035, India (phone: +919706768066; e-mail: arnab.sarma@rgi.edu.in).

II. Literature Review

In the Mumbai City Report, Patankar et al. documented that the location of Mumbai being on the coast puts it at greater risk [2] of sea-level rise, flooding, high winds, cyclones and coastal erosion, due to its flood prone location and the landmass composed largely of reclaimed land. It was forecasted that Mumbai was going to be highly susceptible to global climate change with majority of its population living on the flood prone and reclaimed land. Being on the seacoast, the city experiences a tropical savanna climate with a heavy south-west monsoon rainfall of more than 2100 mm a year. The Risks and Vulnerabilities Plan that is an essential part under the Greater Mumbai Disaster Management Action Plan (DMAP) further envisages specific relief and mitigation measures for Mumbai on infrastructure improvements, contingency plan, land use policies and planning.

Kumar et al. studied 480 km at east coast of India, vulnerable to accelerated erosion hazard adding Tsunami run-up with short term data from remote sensing satellites and long-term data from numerical models to determine high, medium, and low Coastal Vulnerability Index (CVI) [3].

Saravanan et al. found that the oceanography of the Indian continental region is dominated by three seasons viz. SW monsoon (June to September), NE monsoon (October to January) and fair-weather period (February to May) [4]. They also studied the Potential littoral sediment transport along the SE Coast of India [5] in relation to wave activity and beach morpho-dynamics through wave refraction studies and opined that due to the presence of shallow Palk bay, Gulf of Mannaar and the Sri-Lanka Island the south Tamilnadu coast of India has comparatively lesser sediment transport.

Ranger et al. apprehends that 2005-like events will more than double by 2080 with potential increase in risks associated with heat waves, tropical cyclones and storm surges due to Sea Level Rise (SLR), which warrant significant revision in urban development & assimilate climate change adaptation measures [6].

Nicholls et al. illustrated serious concerns on the impact of SLR at London, New York, Tokyo, Shanghai, Mumbai, and Lagos [7].

Cazenave et al. studied causes for SLR based on satellite and in-situ data sets and suggested adaptation to threat, which matches with IPCC AR4 [8].

Balica et al. ranked Flood Vulnerability Index (FVI) in histogram for 9 cities: Buenos Aires, Kolkata (India), Casablanca, Dhaka, Manila, Marseille, Osaka, Shanghai and Rotterdam (Fig. 1). They project Shanghai and Dhaka to be most vulnerable by year 2100 followed by Manila and

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Kolkata, Casablanca, Rotterdam. Buenos Aires and Marseille will remain in the lower positions, Osaka being least vulnerable to floods [9].

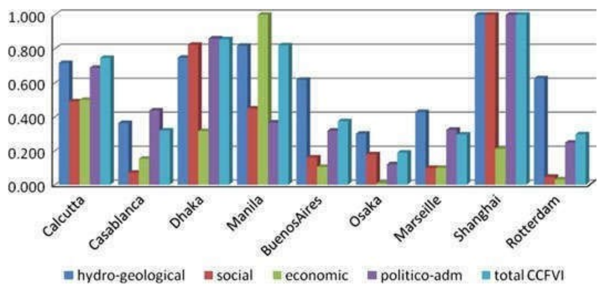

Fig. 1 Total FVI, ranking of coastal cities for different scenarios [9]

Radhika et al. preached evaluating the Significant Wave Height (Hs) on the basis of hindcast wave as inadequate, considered future Hs by downscaling wind information obtained from a General Circulation Model (GCM) run for various scenarios of global warming. Fitting the predicted Hs for next 30 years into Gumbel or Weibull distributions was compared with hindcast and Weibull distribution was found statistically more reliable [10].

Viviek et al. developed CVI using remote sensing and GIS for Southern tip of India at Tamil Nadu. MSS, TM5 and ETM+ from Landsat-1 were used to evaluate the annual shoreline change rate & ArcMap 9.0 was used for mapping the CVI. The southernmost part of India is exposed to the refracted and diverted waves from Sri Lanka [11].

Mahapatra et al. quantified that about 1.6 x 10^6 km of total global coastlines are the most damage-prone from both anthropogenic and natural causes by reviewing the available Assessment Tools and techniques such as CVI, Common Methodology (CM), Synthesis and Upscaling of SLR Vulnerability Assessment Studies (SURVAS) and Dynamic Interactive Vulnerability Assessment (DIVA). The authors found that due to the wind forced coastal circulation and the salinity gradient along the coast, the mean sea level in Bay of Bengal (BOB) is higher in comparison to that at Arabian Sea (AS) [12].

Rana et al. focused on future projections provided by GCMs for Mumbai and suggested that the probability of occurrence of intense rainfall will change in the future [13]. Usually, GCM data generally need to be downscaled and bias-corrected for impact studies. They applied a Distribution-based Scaling (DBS) procedure, with 1975–2004 as a reference period, for bias-correcting and downscaling daily rainfall data from nine global climate projections. Significant positive trend was found for four of the GCM projections. The authors have stressed the need to consider the implications of uncertainties in climate projections for adaptation planning in Mumbai. They advocated the use of multiple projections from a range of available Global Climate Models and Regional Climate Models as a single scenario of future climate is by itself not adequate to inform robust adaptation decisions, which differed from earlier analyses for future scenarios stated in [6]. Nevertheless, there are considerable sources of uncertainties in the results, related mainly to the climate projection ability of describing the probability of occurrence of extreme events. They stressed upon the need to incorporate detailed hydrological impact modelling studies to better assess the future impacts on the study area including climate projections by both hydraulic models of the drainage systems and by hydrological models for the Mumbai region.

Bhaskaran et al. based on satellite altimeter observations highlighted the impact of climate change on variability of maximum significant wave height and wind speeds at the Indian Ocean basin [14]. Data from 1992 until 2012 (21 years) from the eight satellite missions were processed using BRAT at two places, one in BOB and the other in AS. It revealed that the increased wave activity especially in Southern Ocean can generate intense swell field that can modulate and modify the local wind-waves in the North Indian Ocean whereas in the equatorial regions no significant impact of climate change cropped up [14].

Chenthamil et al. combined use of satellite imagery and Water Level Rise (WLR) method for shoreline change analysis at coast of Karnataka, India; using MSS, TM, ETM+ Scanner data from Landsat and GIS for studying the change of shoreline along the Karnataka coast. The shoreline rate of change was calculated by DSAS. WLR and End Point Rate (EPR) was adopted for long term and short-term change analysis respectively. Combination of Remote Sensing techniques and GIS including delineation was acknowledged to benefit semi-automatic determination of shorelines [15].

Changes in shoreline positions at western India were studied by Deepika et al. for a period of 98 years, using multi-dated satellite images and topographic maps [16]. EPR, Average of Rates (AOR) and Linear Regression (LR) were used for shoreline change rate at equidistant transects in four Littoral Cells. Authors concluded that ‘shoreline changes at the Udupi coast’ were consistent with Third Assessment of IPCC and the estimated change in shoreline was found to be in good agreement with values by EPR and LR models and the calculated RMS error was tolerable [16].

Revi earlier studied [17] on the adaptation needs and mitigation agenda for cities (where the urban population is likely to grow by around 500 million over the next 50 years) in India. They considered the likely changes in temperature, precipitation and extreme rainfall, drought, river and inland flooding, storms/storm surges/coastal flooding, SLR and environmental health risks due to climate change. Also, they attempted to explore who within urban populations are most at risk. The study revealed that Climate change is expected to increase the frequency and intensity of current hazards and the probability of extreme events, and also to spur the emergence of new hazards like SLR and new vulnerabilities with differential spatial and socioeconomic impacts. Three mega-urban regions: Mumbai–Pune (50 million), the national capital region of Delhi (more than 30 million) and Kolkata (20 million) will be among the largest urban concentrations in the world. By mid-century, India could have both the largest urban and rural populations of the time. Although over this century the period when for emergence of climate change

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would be an important risk in the Indian subcontinent is unpredictable, especially related to precipitation and SLR there also are considerable uncertainties concerning precise mechanisms and impacts. But it is certain that substantial increase in extreme precipitation (similar to that happened at Mumbai in 2005) is expected over a large area of the west coast. The expected scenario calls for significant revision of urban planning practices across city and neighborhood to integrate flood and climate change mitigation and adaptation measures into day-to-day urban development and services,

Singh et al. raised alarm over the effect of SLR even being at a height of 10-15 m above the Mean Sea Level (MSL). Mumbai city is vulnerable to cyclone. Sea Level Change from 1900 to 2011 were obtained from GLOSS for MSL data, DEM was followed using NASA- SRTM, whereas Ward Maps were taken from Municipal Corporation of Greater Mumbai (MCGM) and the data were analyzed by ESRI ArcGIS10.1 Software for SLR scenario using GIS and its effect on the 167 km coastline of Mumbai City surrounded by the AS to the west, the south by the Harbour Bay and the Thane Creek on the east. Administrative blocks under MCGM were compared for scenarios of SLR up to 1 m, 2 m and 3 m using ArcGIS10.1 software [18].

Unnikrishnan et al. deliberated SLR trends over the period 1993-2012 within the north Indian Ocean. Altimeter data analysis revealed that the rate of SLR is quite spatially homogeneous over most of the north Indian Ocean, reaching values on the brink of global MSL-rise trend (3.2 mm $yr.^{-1}$) estimated over an equivalent period. The estimated trends from both tide-gauge records and altimeter data suggest that the ocean level rose at a faster rate during the last 20 years than for the whole 20th century as a response to global warming. Another possible cause for this SLR acceleration may be the Himalayan glacier melt, reported to increase over the recent decade [19].

Misra et al. studied decadal (LULC) changes in the coastal zone in southern Gujarat, west of India. The area was 30 m deep into Gulf of Cambay exposed to strong semi-diurnal high range tides and associated current with erosion accretion. Shoreline change was analyzed using DSAS embedded in ArcGIS 10.1. Immense eroding trend is noticed due to anthropogenic effects and EPR of erosion was observed to be very high to the extent of 0.54 m/year [20].

Patil et al. by combining numerical and a special wavelet neural network [20] demonstrated predicting site-specific dependable forecasts of SST at six locations in the Indian Ocean over three-time scales (daily, weekly and monthly at AS, BOB, WEIO, EEIO THERMO (off the African Coast), and SOUTHIO produced accurate SST [21].

Saha et al. predicted ocean currents by combination of a numerical model and ANNs. At two deep-water locations (in the northern Indian Ocean near the equator and near the eastern edge of the thermocline ridge where the flow of currents here slowly moves away from the equator) and the results were found to be satisfactory up to 5 days [22].

Rajasree et al. studied shoreline changes along the west coast of India with past data from earlier satellite images and predicted future wave magnitude by running a numerical model simulating data from past 35 years as well as for future 35 years. Computations alternatively done by ANN with the help of past satellite images also established rising trend of erosion but at a smaller rate (1.66 m/yr.) than obtained from the numerically predicted one (2.21 m/yr.) [23].

Sunder et al. compared remote sensing-based shoreline mapping techniques at different coastal stretches of India and concluded that the AWEI is the most consistent index among all the four indices since it is showed more than 80% overall accuracy for all the test sites [24].

The studies [18] were further extended and GIS has been proved to be the finest tool in analyzing the changes due to climate and it was recommended for future studies the DEM with finer resolution should be used [25].

Rajshree et al. furthered their research [23] on straight coastline on central west coast of India to find changes in coastline with different geomorphologic features to predict shoreline changes for different coastal configurations using future climate projections [26]. Comparing predictions by satellite imageries, numerical models and ANN, it was observed that ANN predicted smaller rates than those obtained from the numerical model but higher than from satellite imageries. Near Mangalore Port through numerical modelling it was measured that a rise of 29% in the annual mean significant wave height over a period of next 36 years would contribute to a rise of sediment transport by 109% [26].

Ankita et al. generated satellite derived bathymetry maps at Ameland Inlet at the Netherlands by using Support Vector Regression (SVR) techniques. It was concluded that these free and easily available medium-resolution imageries from Landsat can help in determining long-term coastal analysis [27].

Kulkarni et al. quantified the benefit of skill addition of Regional Climate Models (RCMs) in simulating wind speed, direction and the wind energy & in particular evaluated utility of CORDEX in the parent GCMs. The study area at AS and BOB, on both sides of the Indian coastline were unique among the world's water basins as wind reverse semi-annually, blowing from the southwest during the northern summer and from the northeast during the northern winter. Around 70% of the Indian offshore locations in monsoon would experience mean wind potential greater than 200 W/m^2, as indicated by most of the RCMs and GCMs [28].

The study [27] was repeated in 2018 at the same coast near estuary of a River Gangavali using simple neural network as an alternative to empirical/numerical modelling based on traditional satellite imageries or field observations. Numerical wave model was simulated for waves for past and future time periods of 36 years each [29]. The shoreline changes in the past varied from -2.18 to +2.67 m/year whereas the numerical model indicated that the shoreline changes in future would vary from -2.11 to +3.52 m/year. The mean Hs may increase at a rate of 0.06 cm/year, whereas the maximum one may rise up to 0.38 cm/year. The future mean Hs in 36 years is expected to rise by 15.87% accompanied by a shift in the mean wave direction by 10.270. From past 36 years to future

36 years it was predicted that an increase of 131.7% and 114.3% in the net and gross sediment transportation can take place. It was inferred that the Neural Network can be used to verify future changes predicted by Numerical Model for conformity [29].

Verne et al. [30] investigated the morphodynamical and hydrodynamic characteristics along the coast of Maharashtra running Delft 3D model to understand the nearshore bed level variations driven by seasonal cycle of hydrodynamic environment. The simulation was run for one-year period (2017) to assess the seasonal variation in the nearshore bed region. The sources for inputs like wind and wave, tidal elevation and bathymetry were ECMWF, GEBCO and NHO respectively. The inputs were validated with estimated results from literature and data observed from INCOIS and IHO. The hydrodynamic model was calibrated with temporally varying ECMWF inputs and the model performed satisfactorily as understood on comparing climate parameters like Hs, T and MWD from INCOIS wave rider buoys in Maharashtra, India [30].

The studies by Rajshree [23], [26] were further extended for a combined multicriteria-based CVI evaluation at central west coast of India along with a different team [31]. They assessed CVI, using projected as well as historical climate issues (wind, wave, shoreline changes) for two periods 1979-2017 and 2017-2052 by simulating a moderate global warming scenario executed for uninterrupted, naturally discontinuous, and artificially interrupted coastlines. For the purpose of the studies, MIKE 21SW (DHI) was used [31].

Dhiman et. al. provided an assessment regarding quantification, management and climate change impacts of flood risks in 4 most populated coastal cities in India including Mumbai [32]. Mumbai, being the most populous Indian city, located along the western coast of India, is having 2 large ports in western India and simultaneously known as the commercial and financial capital of India. The megacity ranks as the 5^{th} largest city (in terms of the population) in the globe (2019) and the population is projected to pass 27 million in 2030. Anthropogenic reclamation primarily caused the original seven islets to merge and form the current Mumbai city (Fig. 2). Reasons for inundating also include inappropriate levels of outfalls, the increase in the run-off coefficient due to the urban landscape, the loss of holding ponds due to land development and encroachments on drains and obstructions caused by utility lines being crossed. The yearly flooding in Mumbai incurs huge economic losses due to the economical–social disorientation and associated shutdown, ultimately affecting the economy of the nation [32].

Abadie et al. proclaimed that there is a high degree of uncertainty associated with the potential mass loss of the Greenland and Antarctica ice-sheets and the extent of resultant future SLR [33]. The authors explored the impact of the uncertainty on economic damage due to SLR for 136 major coastal cities by comparing the probability distribution considering the stochastic model of expected damage and risk calculation, for two scenarios. One scenario for relative sea-level projections is the damage under the assumption of no adaptation (the RCP 8.5 scenario from the IPCC Fifth Assessment Report) and the other one is a high-end scenario that incorporates expert opinion on additional ice-sheet melting. The results suggest that it is critical to incorporate the possibility of High-end scenarios into coastal adaptation planning for future SLR, especially for risk-averse decision-making. In the analysis in both scenarios Guangzhou (in China) tops the list and next to Mumbai is New Orleans (in Louisiana, USA) which will face the highest risks. It was found that that among 136 coastal cities across the world, Mumbai is second-most at risk to climate-induced SLR and extreme weather events.

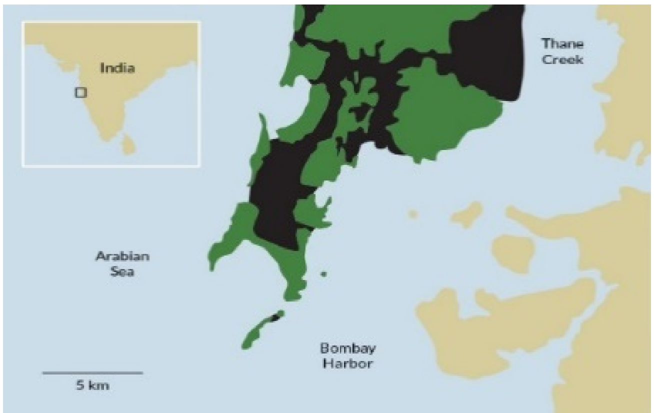

Fig. 2 The original seven islands (green) connected by reclamation (black) in Mumbai [38]

Dhiman et al. developed a systematic approach to link the critical gap between information, knowledge, data and GIS services in coastal cities [34]. They introduced an open-source Web-GIS based decision support framework stated as CMIS, to integrate data and knowledge plus GIS services for the Mumbai megacity. CMIS is developed using the open source platform supported PHP and Map Script. The three key components are – Data Centre (houses different datasets for expert stakeholders), Knowledge Centre (developed for common stakeholders), and Web-GIS based online mapping tool called CMIS Online which enables a user-friendly assessment of coastal resources. It can act as a dynamic mapping application for coastal features, incorporating advanced GIS functionalities. The authors further described the methodology for the existence and implementation of CMIS as a pilot initiative along the coastline. Such initiative can strengthen the institutional framework between associated government agencies, coastal planners, managers, and researchers. The study stimulated the employment of open source coupled GIS techniques, which might enhance the transparency within the allocations and utilization of coastal resources among various end users, and thereby the developed framework can curtail over-exploitation of resources to some extent and could aid the progression towards a more sustainable and resilient urban environment.

Garner et al. stated that as because projections of SLR from individual studies varies from and rather generally higher than upper projections, anticipated by the Intergovernmental Panel

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on Climate Change, in reality very often future SLR remains deeply uncertain and the upper projection windows for the SLR projections are not uniform across different studies. They distrusted the correctness of the research outputs. The widely varying range of these projections reflected gaps in scientific knowledge about the processes that contribute to SLR, reflected in assumptions used to produce projections [36]. Many projections for high emission scenarios from individual studies were found much greater than likely range of 1m of the 21st century SLR given in AR5 [35]. Moreover, due to the additional load from melt ice the SLR is escalating in recent years.

III. Conclusion

From the facts in the foregoing, it can be concluded that thorough research in this field it is necessary to ascertain CVI of coastal places including that in Mumbai.

The processes responsible for the monthly and seasonal variation in the morphology of a beach are controlled by wave, climate, tide and sediment characteristics [3]. In a study for impact of climate change on flood risk in Mumbai it is suggested the likelihood of a 2005-like event with 0.5 m to 1.5 m deep waterlogging in low-lying areas would be more than double by 2080 [6]. Neural Network also was used to conform future changes predicted by Numerical Model at places [29] for shoreline changes [26]. Morphodynamic Investigation along the Maharashtra Coast by running Delft 3D model (when corroborated with INCOIS & IHO), underestimated the net sediment transport and overestimated the total one [31]. For accommodating different risk tolerances under different scenarios, the climate simulator model prescribed by IPCC AR5 (Special Report on Emission Scenarios) at local level [37] reveals that under RCP 8.5 SLR at Mumbai coast is 1.24 m, under RCP 4.5 is 0.94 m whereas under RCP 2.6 with aggressive cuts in the carbon pollution, SLR reduces to be around 0.81 m above MSL (Fig. 3).

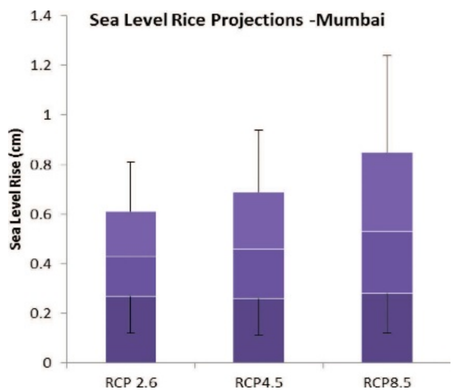

Fig. 3 SLR vis-a-vis Scenarios (Mumbai) [37]

It has been seen that in the later part of the last decade use of Remote Sensing, GIS, Satellite image mapping and computerized models gained more acceptance. It is generally believed that the correctness of the result largely depends on the model chosen for analysis. It is also established that further full-scale dedicated research is required to project the vulnerability of Mumbai due to climate change and its resultant impact on SLR in future decades, when CMIS type tools can be of convenience. It is obvious that more research is required after watching the actual scenario, and taking note of scenario which will arise at Mumbai in future.

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Chakraborty Sudipta, West Bengal, India; December 05, 1957; B.E. civil engineering, University of Calcutta-1978; M. Tech aeronautical engineering, Indian Institute of Technology, Kharagpur,1981; M. Engg hydraulic engineering (coastal engineering & port development), International Institute of Infrastructure, Hydraulic and Environmental Engineering, Delft 1999.

He was Head of Infrastructure Division of Haldia Dock Complex, Kolkata Port Trust under Ministry of Shipping, Govt. of India. Presently a Consultant to Assam Inland Water Transport Development Society, Guwahati, Govt. of Assam for upcoming Ferry Terminals on River Brahmaputra funded by World Bank; and a Research Scholar in, Department of Civil Engineering at The Assam Royal Global University, Guwahati, India. His Publications and presentations include (i) 'Parametric Instability of Beams by Finite Element Method'-The Journal of Mechanical Engineering Science, London, Volume 24, No.4, December 1982; (ii) 'Development of new terminal of a port at west coast of Arabian Sea in India- challenges at the interface of dredging and reclamation 'in Coast and Ports Conference, Australia, 2017; (iii) 'Stability of Reclaimed Soil Mass in Sea from Seismic Consideration' in National Seminar on "Earthquake Hazards", Ministry of Earth Sciences at North Eastern Hill University, Shilong, India, 2020; Book: 'Sea Level Rise: Are We Ready?' 2020; Research interests: 'Finite Element Method', 'Structural Engineering', 'Hydraulic Engineering', 'Impact of Climate Change on Sea Level Rise'. He has reviewed Papers in 'Coasts and Ports Conference, Australia 2017, 2018, 2019.'

Mr. Chakraborty is a Life Member, Permanent International Association of Navigation Congresses, & Indian Water Works Association and a Fellow of Institution of Engineers (India).

Kambekar A. R. Dr. Maharashtra, India; 05th November, 1969, B.E Civil engineering, Amravati University,1991; M. Tech Civil -Offshore Engineering, Indian Institute of Technology, Bombay, 2002; PhD Civil Engineering, Indian Institute of Technology, Bombay, 2010.

He is an Associate Professor in Civil Engineering at Bharatiya Vidya Bhavan's Sardar Patel College of Engineering, Mumbai University. Publications: 'Estimation of pile group scour using neural networks,' Applied Ocean Research, Elsevier, Oxford, 2003; 'Data driven methods to analyze wave buoy observations,' American Society of Civil Engineering, International Workshop on Computing in Civil Engineering, Austin, Texas, 2009; 'Wave simulation and forecasting using wind time history and data driven methods,' Journal of Ships & Offshore Structures, Taylor and Francis, 2010; 'Real time prediction of ocean waves using wind time series, Conference Water 2010, Quebec, Canada; "Wave Prediction Using Genetic Programming and Model Trees," Journal of Coastal Research, 28(1), 43-50, 2012; Research interests-'Infrastructure Engineering, Water Resources Engineering, Offshore, Ocean & Coastal Engineering. He is Reviewer at International Journals ASCE, Elsevier, Actapress, Hindwai.

Dr. Kambekar is Member Board of Studies Civil Engineering at University of Mumbai, Dr. Babasaheb Ambedkar Technological University, Raigad, Maharashtra, India and NMIMS, MPSTME Deemed University, Mumbai.

Sarma Arnab Dr. Assam, India, October 17, 1966; B. Tech. civil engineering (Kelappaji College of Agril. Engineering & Technology, Tavanur, India, 1990; M. Engg. Irrigation water management (College of Technology & Engineering), Udaipur, India, 1993; Ph.D. water resources engineering (Mendel University, Brno, Czech Republic 2001).

He is the Head, Department of Civil Engineering, Royal School of Engineering and Technology, The Assam Royal Global University, Guwahati, India. He has 37 publications and one Book Chapter to his credit. His research interests are in the fields of Irrigation, Catchment Hydrology, Climate Change, Soil Erosion, Erosion and Sedimentation.

Dr. Sarma is a Fellow of Indian Association of Hydrologists (IAH) and Indian Water Resources Society (IWRS) besides being Members of American Society of Civil Engineers (ASCE), International Association of Hydrological Sciences (IAHS), Institution of Engineers, India, International Association of Engineers (IAE) and Assam Science Society (ASS).

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Uncertainties in Prediction of Future Sea Level Rise Due to Impact of Climate Change

Chakraborty Sudipta[1*], A. R. Kambekar[2] and Sarma Arnab[1]

[1]*Civil Engineering, The Assam Royal Global University, Guwahati, India.*
[2]*Civil Engineering, Sardar Patel College of Engineering, Mumbai University, Mumbai, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Opinion Article

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ABSTRACT

On reviewing the development of the research methodologies on climate change and sea level rise during the last two decades, it is observed that the assumed scenarios for apprehending the rise in global temperature are grounded on a lot of uncertainties. The real-time data varies from IPCC's predictions. The gradual transition on the emission pathway scenarios from SRES (2000) till RCPs in AR5 of IPCC depicts the conceptual difference between the two concepts in scenarios. SRES represented detailed socio-economic-based scenarios, but RCPs are based on the capacity of a gas affecting the change in energy in the atmosphere due to GHG emissions known as Radiative Forcing. Considering the possible range of the radiative forcing values in 2100, AR5 of IPCC considers the four RCPs numbered as 2.6,4.5, 6.0 and 8.5 as per greenhouse gas concentration trajectories (not emissions). The present condition of melting of ice sheets at Antarctica and Greenland is quite high and it is understood that such melting will continue. Even in a situation, if the anthropogenic emission of GHGs is immediately stopped, the self-sustained melting will continue. Models so far being based on numerical and probabilistic approaches are expected to undergo abrupt change because of the current inconsistent ice sheet dynamics. Considering deep

**Corresponding author: E-mail: diptasu@gmail.com;*

uncertainty in socio-political and economic changes amongst nations, the importance of usability of model hierarchy for the complex science of climate change is becoming unforecastable, in the prevalent ice dynamics during accelerated warming situations. In reality, the predictions are becoming less reliable. Possibility of the scenarios likely to be changed are apprehended during the advent of CMIP6 and the variations in contributing factors in the form of SSPs in the upcoming IPCC AR6, in 2022 and it is indicated that the research may take a new turn. A multidisciplinary approach to research with minimum uncertainty ina more precise and finer manner is the need of the day.

Keywords: SRES; RCP; SSP; IPCC; AR6.

ABBREVIATIONS

SRES : Special Report on Emissions Scenarios
IPCC : The Intergovernmental Panel on Climate Change
AR5 : Assessment Report 5
RCP : Representative Concentration Pathway
GHG : Green House Gas
SSP : Shared Socio-economic Pathways
AR6 : Assessment Report 6

1. INTRODUCTION

Historically, it reveals from real-time data that the projected and observed data for sea level rise widely varies from region to region [1]. There are variations in sea-level change projections which are more often uncertain [1]. The patterns of predictions largely vary because the determination of projections stands upon a lot of uncertainties in the complex geophysical processes. Over the years, the projections of sea level rise were based on certain assumed scenarios on the severity of global emissions of Greenhouse gases. [1]. The scenarios have transformed from the initial assumptions made in SRES, and is going to be re-evaluated in upcoming SSPs, which till now are intermittently based on RCPs. However, as these scenarios depend upon societal decisions and the needs of human civilization, they vary from nation to nation.

There are four categories for sources of uncertainty viz. from (1) ice-sheet (2) anthropogenic (3) limitations of model/data and from (4) atmosphere and ocean. The transition from SRESs to SSPs routed through RCPs along with various approaches to resolving the uncertainties has been reviewed and it is felt that societal decisions on scenarios will majorly influence the actual real-time sea-level rise. The recent concept of partitioning the uncertainties may perhaps even lead to more accuracy in projections.

2. REVIEW

The Intergovernmental Panel on Climate Change (IPCC) considered four families of emission pathways in SRES (special report on emissions scenarios). A distinctly different storyline for each family was assumed in the direction for future developments to make each of the four storylines different in increasingly irreversible ways. At the beginning of the millennium, climate change likely to take place in this century has been evaluated when it has been acknowledged by scientists that the scenario will depend on how human societies would develop in terms of demographics and economic development, technological change, energy supply and demand, land use, regional development etc. [1].

In 1995, Coupled Model Intercomparison Projects (CMIP) was established for studying the output of general circulation models (GCMs) as under World Climate Research Program (WCRP) [2]. The initial one was modified in 1996 as CMIP2 (1996) and revised to CMIP3 (2010), whereas, now CMIP6 is in the offing after IPCC's Fifth Assessment Report (AR5) considered CMIP5 (2013).

Due to complex interactions within the climate system, human activities have led to unprecedented changes in the earth's atmosphere, though it is difficult to clearly delineate the characteristics of climate change associated with natural and anthropogenic forcing. There are credible evidences to show that such changes have the potential to influence earth's climate. It is also stated that significant differences exist at regional levels in spite of the fact that meteorological data has recorded overall warming around the earth [3]. Human activities like the emission of greenhouse gases or land use changes result in external forcing. It is generally believed that external forcing-induced climate change is predictable. But in reality, such predictions have limitations as population change, economic policy, technological changes are hardly accurately predictable. Because of the unpredictability itself, climate projections are based on carefully constructed assumed scenarios [3]. As an example, particularly over the northwestern parts of India, most models project enhanced precipitation during the monsoon season, wherein the magnitudes of projected changes differ considerably from one model to the other [3].

From a sustainability point of view, under United Nations Human Settlement Programme (UN-HABITAT), it is observed that the resulting sea level rise due to anthropogenically caused global warming is the largest challenge in our planet. It is also pointed out that severe weather risk and seawater rise pose increasing threats in coastal areas. It is indicated that threat to cities due to sea level rise is only one part whereas more extreme weather patterns such as intense storms are another [4].

Compounding uncertainties in Sea Level Rise Assessments have been uncovered stating that there are many barriers that impede adaptation to climate change, including lack of data, information, and resources; inflexible institutions; perceptions of risk; lack of funding and leadership; scale mismatches; and above all the uncertainty [5].

Unless the current trend in the rise of global mean temperature is reversed, the increasing Global mean sea level will continue to rise beyond the year 2100. It is established that sea level rise over the last century has been dominated by ocean warming and loss of glaciers. But sensitivity suggested important contributions should also be expected from the Ice Sheets at Greenland and the Antarctic. Ice Sheet at the Antarctic holds more than half of Earth’s freshwater and is by far the largest potential source for global sea-level rise under future warming conditions. The rising trend of Global mean temperature may decline slowly due to inertia in climate and global carbon system if greenhouse gas emissions reduce. But uncertainty remains on how much sea-level commitment is expected for different levels of global mean temperature increase. It is opined those additional strategies to better constrain the sea-level commitment will be necessitated [6].

While formulating a proposal to avoid conflict between sea level rise and the coming uncertainties, it is widely acknowledged that climate change will alter the world over the coming century. However, it is unclear how different regions of the globe will be affected by this change. No straight prediction is possible for some particular place, in terms of heat and precipitation. The melting of the great ice sheets and glaciers will continue, and perhaps, melt even faster. As a result, the rise in oceans will persist over the next century up to order of one meter [7].

Climate and its elements are undoubtedly the most important factors for all types of life forms on the earth, as evidenced by erratic precipitation, glacier melting, bleach of coral, shifting of tree lines including rising in sea level [8]. The anthropogenic causes are already acknowledged and newer complexities in climate scenarios are also well-known, because of their variation from the past. Considering records through modern instrumentation, historical temperature analysis, and global precipitation studies, there is a need for a clear discrepancy between climate change and global warming [8].

Lange (2014) documented various aspects of uncertainties in sea level change. They illustrated that global sea level is estimated using averaged measurements from a worldwide network of coastal tide-gauges or from satellite-borne instruments. Being the worldwide average, it does not appear to be fruitful for local coastal evaluation. Rather, local relative sea level measured at specific locations depend upon the direction and rate of movement of the underlying land (tectonic change) in different parts of the world. Local sea-levels are rising or falling and from geological evidence over long periods of time (millions of years), the sea level changes are assessed. According to them, however, these long-term changes suggest that any sea-level rise in response to temperature increase decelerate rather than accelerate over time. Based on the past, it is stated with certainty at different locations around the world, that future sea-level will continue to change at differing rates and in different directions. The authors mentioned two steps - understanding of past rates of change, present environmental conditions and theoretical analysis and projection of likely changes. The maximum rate and duration of natural sea-level rise are recorded to be about 30 mm/year over periods of a century and typically less than 10 mm/year, has been taking place over the last 10,000 years as slow global sea-level rise [9].

Trenberth et al. (2014) stressed upon that there is an imbalance in energy flows in and out of the earth system. They stated that "Warming" being the phenomenon of extra energy, can manifest in many ways like rising of surface temperatures, melting Arctic Sea ice, increasing the water cycle and altering storms. It was inferred that most of the excess energy goes into the ocean. They focused on the need to monitor the energy imbalance with direct measurements to find where the energy goes and quantifying how climate change is manifested. They strongly opine key issues for Earth from an overall energy standpoint are the actual energy imbalance at the surface and top of the atmosphere. While assessing the exchanges among the climate system components (atmosphere, ocean, land, and cryosphere) and the changes in phase especially of water involving latent energy (ice, liquid, and vapour), they also agree that a major part of the anthropogenic heat (90%) is absorbed in the oceans and only the remaining goes for melting of ice, both terrestrial and at sea [10].

Unnikrishnan et al. (2015) documented the trends in Sea-level-rise based on estimates derived from satellite altimeter and tide-gauge data of the Indian coasts for the last two decades. From Altimeter data analysis during 1993–2012 period, they noted that the rate of sea-level rise (3.2 mm/year) is rather spatially homogeneous over most of the north Indian Ocean and matches with the trend of mean sea-level's global rise in the corresponding period. They also recorded the notable exception in the northern and eastern coasts of the Bay of Bengal, which experienced larger trends (5 mm/year and more). Finding the trends derived from altimeter data as higher than those estimated from tide-gauge records over longer periods, they targeted for an improved understanding of the mechanisms behind this accelerated sea-level rise recorded over the past two decades. The nonconformity was highlighted as uncertainties between the methods of measurement. They opined that the modeling concepts may land up afresh depending on how the meltwater reacts with unforeseen atmospheric changes. The major caveat to derive the reliable multidecadal sea level rise on Indian Ocean is believed to be lack of long-term sea-level observations. Satellite altimetry provides high-resolution sea-level measurements since 1992 but that is inadequate for reliable estimates of regional sea-level rise trends [11].

Cozannet et al. (2015) during evaluating uncertainties on flooding due to the rise of sea level observed that the frequency of coastal flooding events has changed. They highlighted the need for accounting variability of storm surge patterns and sea-level rise to provide quantitative insight into the relative importance of contributing uncertainties over the coming decades accurately. Considering IPCC projections for sea level rise, a global sensitivity analysis was applied on an urban low-lying coastal site located in the north-western Mediterranean, where the yearly probability of damaging flooding could drastically grow after 2050 [12].

Sorokin Lionid et al. (2015) while investigating on European Airports reiterated their concern about radical uncertainties in sea level rise. The importance of climate scientists' divergent opinions about the sea level rise and its consequences for decision-makers was highlighted. The team opined those new scientific uncertainties on SLR's evolution essentially meant a lack of reliable scientific knowledge which in turn is linked with the decision-makers' liability resulting from scientific uncertainty. Considering baseline scenarios in IPCC AR5 for the increase in global mean surface temperature without additional mitigation, they called for internationally synchronized fast mitigation and preventive measures to combat with the detrimental situation [13].

Oddo. C. Perry et al. (2017) stressed upon the hypothesis of Decision Making under Deep uncertainties in storm surge and sea-level rise projections for risk analysis from the point of view of Operations Research. They stated that the flood adaptation model produces potentially myopic solutions when formulated using traditional mean-centric decision theory as the risk-based adaptation strategies remain silent on certain potentially important uncertainties. They explained the concept of 'Deep uncertainty' as a condition in which analysts cannot correctly anticipate: (1) the appropriate models for interactions amongst variables, (2) the probability distributions and/or (3) the desirability of alternative outcomes. They found deep structural uncertainties that have large effects on the model outcome, with the storm surge parameters accounting for the greatest impacts. Global sensitivity analysis effectively identifies important parameter interactions that local methods overlook, which could have critical implications for flood adaptation strategies [14].

Baker Alexander et al. (2017) reckoned that the WAIS (West Antarctic Ice Sheet) is going through rapid disintegration and also noted published projections as widely divergent. To quantify the deeply uncertain contributions from West Antarctic Ice Sheets, they presented a set of probabilistic semi-empirical models of the climate and sea-level contributions from thermal expansion along with contributions from the ice sheets at Antarctic & the Greenland including those from the glaciers and the small ice caps. Three projections following RCP8.5 based on three collapse scenarios at WAIS are (i) no collapse (0 cm), (ii) mid-range estimate (79 cm in 2100) and (iii) high case (3.3 m). Full disintegration WAIS within a couple of decades were thought. They found a high range of deep uncertainty in sea-level projections (Fig. 1), as the range usually involves both the estimates and a probabilistic construal of the surrounding uncertainties. It is noted that the uncertainty of the sea-level projections represented in CMIP5 climate models at "open ocean" increases while approaching nearer to the coast. The climate models can predict sea-level rise explicitly due to changes in ocean circulation and density because of global thermal expansion. However, the contributions from land water storage, glaciers and ice-related components are determined using offline models considering boundary conditions derived from temperature and precipitation. The models do not always represent important coastal processes, like sedimentation and erosion changes associated with changes in waves and tides, etc. Compilation of the uncertainties in mean sea-level projections is seen to be strongly depending on the emission scenario globally (Fig. 2). It was emphasized by them that the future climate forcing will to a large extent be dependent on future decisions of human [15].

Mach et al. (2017), taking stock of recent advances and challenges in 'Next Generation of Assessment' acknowledged deep uncertainty and reviewed the climate change assessment. They relied upon quantitative/qualitative evidence, expert judgements, exploring futures and interactions between experts and decision-makers. They opined that in the current era of climate and broader global change, integrative assessment considering both opportunities and pitfalls can bolster decisions about uncertain futures for sustainability. The need for integrative assessment is identified to enlist what is known and what is not [16].

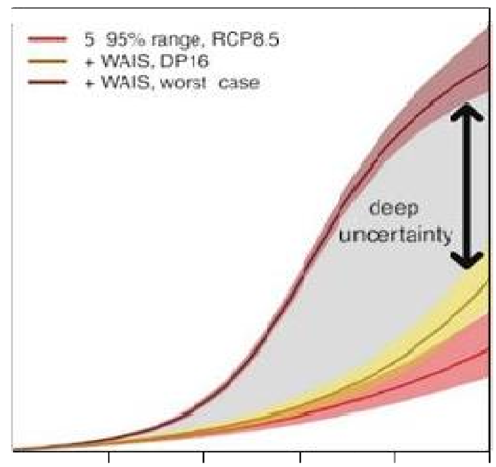

Fig. 1. Future sea-level projections including a deeply uncertain contribution of the WAIS [Scientific Reports volume 7, 3880 (2017)]

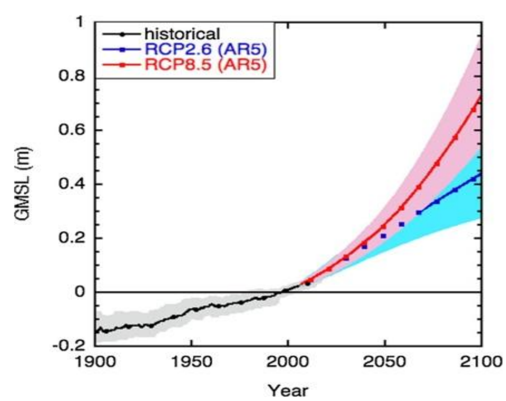

Fig. 2. Uncertainties in GMSL compiled over the period 1900–2100 [Church et al. (2013)].

2.1 Controversies

Garner et al. (2018) strongly noted the fact that upper projection windows for SLR projections are not uniform across different studies. They discoursed that very often, future SLR remains deeply uncertain in reality. Projections of SLR from individual studies varies from one another and rather generally found higher than the upper projections assessed by IPCC. The accuracy of the research outputs was expressed as ambiguous. The authors categorically raised doubts, and distrusted the correctness of the research outputs. The widely varying range reflected uncertainties in scientific knowledge related to the processes contributing to SLR, reflected in assumptions used to produce projections [17].

Le Bars Dewi (2018) explained that the uncertainty of total sea level projections obtained by adding the contributions from thermal expansion, glaciers, and ice sheets', depends on the correlation between the uncertainties of the contributing factors. In an attempt to model the correlation structure and its time dependence, the author observed that the correlation primarily arises from uncertainty of future global mean surface temperature which predominantly correlates with almost all contributors. They acknowledged the acceleration of the sea level rise in this century. However, they mentioned that unfortunately numerical models, based on a physical understanding of the relevant processes of the complex systems like the Earth's climate, do not yet include all of the important processes driving future sea level. It is highlighted that glaciers and ice caps are large enough to contribute to sea level rise, but the main physical processes determining their response to climate change are still uncertain. The long-time scale of adjustment and sensitivity to small circulation and temperature biases still make it challenging to include them in fully coupled models. The problem of dependence of sea level contributors is also more di□cult to understand because it is not about events that correlate in time, for which we have a good intuition, but about events that correlate in the ensemble of possible futures that is a more abstract concept [18].

Mehta et al. (2019) introduced the heuristic of the 'above', 'middle' and 'below' to understand the uncertainty perspectives on climate change in Indian perspective. They studied sea level rise at three places viz. at Sundarbans, at Kutch and at Mumbai. The authors referred the cataclysmic flooding over Mumbai on July, 2005 due to about 944 mm of rain poured within 24 hours. It has been acknowledged that due to macro trends such as temperature extremes and sea level rise climate science is dealing with uncertainties. They barely appreciated understanding the effects at the local level due to downscaling challenges and also intersections with other drivers of change. They emphasized on the 'envelope of uncertainty' that intersects with political, social, cultural, economic and scientific domains [19].

Kopp et. al. (2019) while evaluating the usability of recent researches, identified that sea level rise involves natural and human systems with long lags, irreversible losses and deep uncertainty in anthropogenic emissions, ice sheet dynamics, variability in tides and storms. They opined that given the political, economic, and technological complexities involved, there is no sacrosanct way of estimating the relative probability of different future emissions. Accounting for deep uncertainty involves interactions of sea-level change, geomorphology, socioeconomics, human responses, risk management, adaptation strategies, political and economic viability etc. The usability of sea-level science being a pressing concern warrants finding long-term sea-level projections by grappling with the stated deep uncertainties. More clarity and stable understanding of the relationship between long-term trends and the impacts of short-lived extreme events, and the ways in which the physical coast responds to increasingly frequent flooding is the prime need of the day. It is also stated that it requires more cognizance of the political economy [20].

Kopp et al. (2019) argued for management of the risks of sea level rise and explained in their paper about the two increasingly well understood forms of ice□sheet instability, i.e., MISI (Marine Ice Sheet Instability) and MICI (Marine Ice Cliff Instability). Because of limited scientific agreement on the key conceptual models, they mentioned 'Deep Uncertainty' to be same as 'Ambiguity'. The inherent uncertainties related to impacts of sea-level rise obtained from Probabilistic Approaches, Dynamic Ocean Circulation Model, Bathtub model for inundation has been discoursed. Interestingly, the extent of uncertainty has been explained by equating it with gambling. For illustrating the implication, it has been commented that in general, all else being equal, humans exhibit a preference for the less ambiguous gamble [21].

Slater et al. (2020) recently found that due to ice dynamics in Antarctica and surface melting in Greenland, the ice-sheet losses track with the upper range of sea-level predictions, stated in the IPCC Fifth Assessment Report. They impressed that short-term variability in the atmosphere, oceans and climate must be accounted in the Ice-sheet models for accurately predicting sea-level rise. They mentioned that Ice dynamic contributions were derived from ice-sheet models forced by, but not coupled to, atmospheric and oceanic model outputs. In this way, the atmosphere and ocean can impact the ice sheet but not vice versa. Advances in ice-sheet modelling are expected in 2022 through ISMIP6 (Ice-sheet Model Intercomparison project for CMIP6), which will deliver process-based projections forced by output from coupled atmosphere–ocean GCMs in AR6 of IPCC report [22].

Garbe et al. (2020) recently documented the hysteresis of the Antarctic Ice Sheet mentioning that a comprehensive stability analysis of the Ice Sheets at the Antarctic for different amounts of global warming was not available so far and they found that the Antarctic Ice Sheet exhibits thresholds, on the multitude of temperature, beyond which ice loss is irreversible. They observed that the ice sheet’s temperature sensitivity is 1.3 meters of sea-level equivalent per degree of warming up to 2 degrees above pre-industrial levels. Between 2 and 6 degrees, this will almost double to 2.4 meters per degree of warming and for per degree of warming between 6 and 9 degrees would increase to about 10 meters. More than half of Earth’s freshwater resources are held by the Antarctic Ice Sheet which comprises an ice mass equivalent to 58 m of global sea-level rise. Its future evolution and the associated sea-level change are therefore of profound importance to coastal entity ecosystems and economies. It will be determined by the interplay between a number of negative (dampening) and positive (amplifying) feedbacks. The largest uncertainty in projections of future Sea level rise is constituted from unknown mass loss from the Ice Sheets at Antarctic [23].

Rander et al. (2020) reiterated that disregarding the seriousness of the risk of climate change will be too dangerous. They reported their findings from their new climate model Earth System Climate Interpretable Model(ESCI MO). They stated that for global warming, the earth has already past a point of no return. They observed that even if globally the society stops all emissions of man-made GHGs immediately, self-sustained melting of ice will continue for hundreds of years. The report stated that melting (in ESCIMO) is the result of a continuing self-continued rise in the global temperature. Global warming is the combined effect of physical processes viz. melting of the Arctic ice, increase of water vapour (driven by higher temperatures), and variation of GHG concentrations in the atmosphere. They have categorically mentioned that huge amount of CO2 is required to be extracted from the atmosphere to stop over the self-sustained warming. They stated that rise in water vapour in the atmosphere and the further rise in the temperature which causes increased release of carbon from melting permafrost are due to anthropogenic causes. At this juncture in plain language, it means that 'There is nothing we can do to stop the oncoming effects of climate change' [24].

Maher et al. (2020) clarified that there is no single unique hierarchy and no one model is suitable for all purposes. A suitable model hierarchy needs to be constructed based on the key scientific questions of interest and even for a given scientific problem, individual scientists will make different, perhaps equally defensible, choices. Their confidence in global warming projections does not yield from blind faith in GCMs output; rather fundamentally supported by basic physical laws. However, those laws have little quantitative predictive capability for Earth's climate. At the other extreme, when comprehensive models are forced into the warmer regimes that may lie in our planet's future, comparing parametrizations is difficult. The suggested purpose of the model hierarchy is to provide a pathway connecting robust physical laws to a complex reality. Even it was declared by the authors that, arguments remain if only a few are useful whereas all models are wrong [25].

Haasnoot et al. (2020) narrated about the large uncertainty on how potential ice-mass loss from Antarctic large can rapidly contribute to rise in sea level during the second half of this century. They also explained the impact of sea level rise from the said ice-mass loss on the coastal adaptation strategy of the low-lying country like The Netherlands. As sea levels rise faster and higher, they forecast that sand nourishment volumes to maintain the Dutch coast in 2100, may increase 20 times larger than to date. The world-renowned storm surge barriers will need to close at increasing frequency until closed permanently. Intensified saltwater intrusion will reduce freshwater availability while the demand will be rising. Anticipating deep uncertainty, they inferred that high SLR scenarios help to enable timely adaptation and to appreciate the value of emission reduction and monitoring of the Antarctica contribution to SLR [26].

Pattyn et al. (2020) published their view that Ice Sheets at the Antarctic are losing mass at an accelerating pace, which is likely to continue over the coming decades and even centuries. For unmitigated scenarios, they expressed their concern on the uncertainty about how fast and upto what extent Antarctica will contribute to sea level rise. They also mentioned the role of bed bathymetry and the relation between global warming ocean dynamics. They felt that linear extrapolations of present-day observed melt rates are assumed because of uncertainty only. Mostly, focusing on unmitigated climate scenarios, such as Representative Concentration Pathway (RCP) 8.5, simple parameterizations of ice-ocean melting rates are generally applied. They suggested to organize large international intercomparison projects to attain accuracy in the representation of physical processes in current ice sheet models [27].

Gregory et al. (2020) studied the evolution of the Greenland ice sheet under a range of constant climates (typical of those projected for the end of the present century) using a dynamical ice sheet model coupled to an atmospheric general circulation model, found an irreversible large future decline of the ice sheets at Greenland. They studied the multimillennial future evolution of the Greenland ice sheet for various magnitudes of anthropogenic climate change in experiments with constant climates using an AGCM interactively coupled to a dynamic ice sheet model. They also pointed out snow albedo as a particularly important uncertainty considering that removal of the ice sheet is reversible with the highest choice of albedo [28].

Horton et al. (2020) recently documented the variability of GMSL (global mean sea-level) projections obtained from various studies. They observed that considering the same emission scenario even has led to confusion amongst decision-making communities because of variation in results. They highlighted that under Representative Concentration Pathway (RCP) 2.6, a team of 106 experts projected a likely (central 66% probability) of GMSL rise (relative to 1986–2005) upto 0.30–0.65 m by 2100 and 0.54–2.15 m by 2300 respectively. It is opined that to make informed mitigation and adaptation decisions, knowledge of the uncertainties related to sea level rise are vital. They also pointed out that the same team of experts projected a likely GMSL rise of 0.63–1.32 m by 2100, and 1.67–5.61 m by 2300 under RCP 8.5. The Ice Sheets at Antarctic and Greenland being the largest potential contributors to GMSL rise, experts identified the Antarctic Ice Sheet as the greatest source of uncertainty which accounted for 23% of responses for 2100 and 21% for 2300. They invited the experts to explain about their greatest source of uncertainty under both RCP 2.6 and RCP 8.5 for their estimates for 2100 and 2300. To avoid biases in influencing respondents' opinion the authors categorically decided to use open-ended questions about their sources of uncertainty and resources regarding sea-level rise estimates. Under two temperature scenarios from the upper and lower extremes of the RCP 2.6 and RCP 8.5, the anticipated GMSL change for centuries during the periods 2000–2100 and 2000–2300 are presented (Fig. 3) [29].

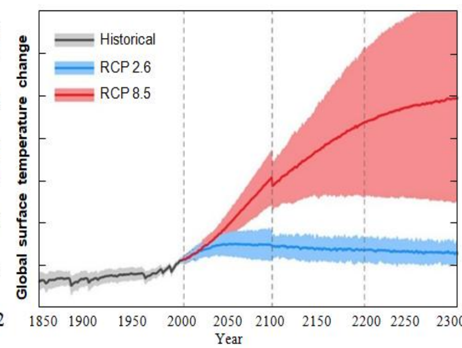

Fig. 3. Global annual mean surface air temperature projections correspond to the lower (RCP 2.6; blue) and upper (RCP 8.5; red) greenhouse gas scenarios modified from IPCC AR54 [29]

Wal et al. (2019) indicated the contribution of each GMSL term to the total variance in projected sea level change over the twenty-first century (Fig. 4). As a matter of fact, combination of melting of glaciers and ice caps along with thermal expansion of the ocean, the dynamics of glacier is certainly going to change. An increase in snow content at any place, will steepen the surface gradients near the edge of the Ice Sheet. Discharging more icebergs into the ocean glaciers will flow faster, and as a consequence, this will negate any impact of the increased snowfall, in mitigating sea level rise. It is opined that because of these factors, the Ice Sheets are vulnerable to rapid melting, which may raise sea level upto 3.3 m within 500 years. Such rates are common in the geological record.

However, the authors commented that these dynamic behaviours are too difficult to predict by simulating even by our most complex computer models. Climate models are not yet characteristically joined to glacier and ice sheet models. An additional uncertainty remains as the impact of freshwater fluxes from melting land ice on the ocean circulation is not yet precisely simulated [30].

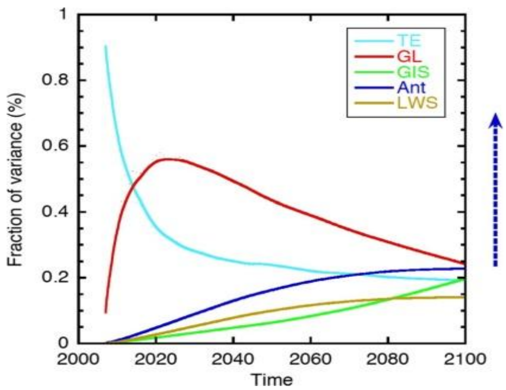

Fig. 4. Relative contribution of thermal expansion (TE), glaciers (GL), the Greenland ice sheet (GIS), Antarctica (Ant) and land water storage changes (LWS) The dotted blue line indicates qualitatively the increase in the dynamic contribution of the Antarctic ice sheet if marine-based sectors of Antarctica collapse [30]

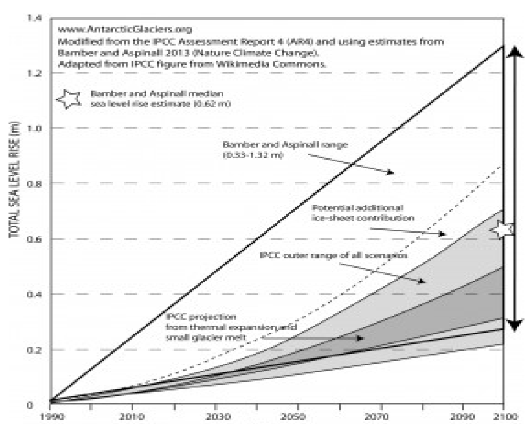

Fig. 5. Comparison of projection for Sea level rise to 2100 [Source: (antarcticglaciers.org June 2020)]

2.2 Assurance

Bamber and Aspinall (2013) to untangle the existing thorny problem modified the IPCC sea level rise estimates and assumed a uniform rate of sea level rise, (Fig 5). They pooled different assessments in order to reach a consensus from numerous experts on likely sea level rise by 2100. The authors considered an increase of 3.5°C above pre-industrial temperatures to match a mid-range carbon emissions scenario. The average rate of rise in sea level was found to be 5.4 mm per year by 2100 AD as agreed upon by these experts from just the Greenland and Antarctic ice sheets. With 62 cm being the average estimate for sea level rise by 2100, combining the effect of melting of glaciers and ice caps in addition with thermal expansion of ocean ; Bamber and Aspinall came out with a range of 33-132 cm. It is still uncertain, but according to them it is the best estimate till now [31].

2.3 Partitioning

Marzeion et al. (2020) recently came out with partitioning the uncertainties from five different sources with the aim to find a more precise assessment. These are: (1) glacier model uncertainty, including uncertainty from any downscaling of atmospheric conditions internal to the glacier model, which causes any two glacier models to project different glacier evolution even if the boundary and initial conditions are identical; (2) climate model uncertainty, which causes two GCMs to respond differently to identical radiative forcing, and which enters the glacier model projections through the boundary conditions (when calculating the surface mass balance); (3) scenario uncertainty, which reflects the uncertainty of the future radiative forcing affecting the GCM projections; (4) internal climate variability, that is, natural fluctuations of climate that arise without any changes in the radiative forcing of the climate system; and (5) uncertainties in the glacier inventory, such as initial glacier volume and area. The remaining four being independent, the scenario uncertainty (3) is conceptually different from the other sources of uncertainty, instead of a lack of knowledge about it, or approximations from natural dependent on future decisions from society, the authors considered the total variance across the ensemble as

$$\text{Variance}_{tot} = \text{Variance}_{gla} + \text{Variance}_{GCM} + \text{Variance}_{RCP} + \text{Variance}_{nat},$$

Where Variance_{gla} is the variance across different glacier models, Variance_{GCM} is the variance across different GCMs, Variance_{RCP} is the variance across different RCPs, and

Variance $_{nat}$ is the variance caused by natural variability. They predicted that overall, 18 % of their ice mass will be lost by the glaciers in a low-emission scenario, whereas in a high-emission scenario, the loss will be around 36% contributing roughly about 79 or 159 mm of rise of sea level by 2100 [32].

3. CONCLUSION

Detailed diverse information on climate, society, economy, adaptation and mitigation are required to predict future climate change impacts. IPCC AR5 suggests a global RCP-SSP-SPA Scenario framework considering Representative Concentration Pathways, Shared Socio-economic Pathways, and Shared Climate Policy Assumptions. There are not many such applications of this new global framework perhaps because of the challenge of multidimensional complex changes and the scale thereof. Combining both expert-based and participatory methods, one multi-scale integrated hybrid scenario approach was applied in three deltas (i) the Volta delta (Ghana), (ii) the Mahanadi delta (India), and (iii) the Ganges-Brahmaputra-Meghna (GBM) delta (Bangladesh/India). Combined with three SSP-based socio-economic scenarios (SSP2, SSP3, SSP5) a climate scenario encompassing a wide range of impacts (RCP8.5) were generated. Minimum intervention, System efficiency enhancement, Economic capacity expansion, and System restructuring -these four-adaptation policies were considered. the importance of multi-scale (combined top-down and bottom-up) and participatory (joint expert-stakeholder) scenario methods for combating uncertainty in adaptation decision-making was established [33].

While the entire planet is under threat, the seriousness of the risk of climate change are certainly too dangerous to be disregarded. From the foregoing collection of information from randomly selected scientific papers published in last two decades, it is concluded that deep uncertainties remain in the research of climate change and the resultant sea level rise. From the chronology of emission scenarios considered in SRES to RCPs in AR5 and further upcoming transition to SSPs in AR6, along with the advent of CMIP6 and also the current scenario of fast melting of ice sheets at Antarctica and Greenland reaffirms the complexity and uncertainties. Climate Science being undoubtedly a very complex multidisciplinary subject, varying reports from different schools of thought of groups of scientists and their considered models has re-established the uncertainty to a great extent. It is hoped that some clue for newer research approaches may be obtained from AR6 of IPCC. Because of accelerated melting in Antarctica and Greenland, the following are of to be noted as matter of utmost concern:

- ‘There is nothing we can do to stop the oncoming effects of climate change’- (Rander et al., 2020) pessimistically opines;
- The disputes persist if only a few are useful whereas all models are wrong (Maher et al., 2020).
- There are ups and downs in control on gigatons of carbon dioxide -despite the axiom that climate change is number one threat to global population.
- Production of oil coal and gas must fall by 6% per year to keep global heating under target until 2030, as agreed in the Paris accord.
- But nations are planning for 2% production increases per year. G20 countries from coronavirus recovery are funding 50% more to fossil fuels than to clean energy.
- Fact remains that the world is doubling on fossil fuel- Great Barrier Coral Reef is deteriorating from World Heritage.
- Uncertainties in ocean circulation models, barotropic vorticity, escalating heat call for more finer precise research to arrive at an optimized adaptation strategy.
- Such unresolved uncertainties raise the question whether the research on sea level rise is going to take a new turn in the ensuing decade starting from 2021.

It is felt that the uncertainties and turns on research will predominantly be dependent on societal decisions i.e., on the sanctity of the scenarios which are going to take place.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Effect of Climate Change and Sea Level Rise Along the Coastline of Mumbai in 2050-using MIKE 21

Chakraborty Sudipta[1,*], Kambekar A.R[2], Sarma Arnab[3]

Abstract

Sea-level rise being one of the most significant effects of climate change have grabbed the attention of the world. Although the exact forecast of rise of sea level remains uncertain, many projections for high emission scenarios from individual studies were found much greater than likely range of 1 m of the 21st century SLR given in AR5 of IPCC. Moreover, due to the additional load from melt ice the Sea Level Rise is escalating in recent years. As per IPCC AR5 (Special Report on Emission Scenarios) climate simulator model at local level SLR at Mumbai coast is 1.24 m, 0.94 m, 0.81 m above MSL under RCP 8.5, RCP 4.5 and RCP 2.6 respectively.. Vulnerability of Mumbai to Sea Level Rise ranks 2nd amongst 136 coastal cities in the world, while Guangzhou (in China) tops the list and next to Mumbai is New Orleans (in Louisiana, USA). Mumbai being a very old reclaimed city with antique drainage system is flood-prone in monsoons. Being the Financial Capital of India further inundation arising out of Sea Level Rise is a matter of grave concern. In this paper the expected Sea Level Rise at the coast of Mumbai in 2050 has been attempted to be determined by the climate change tool using Grinsted's method with the help of Mike 21 FM HD Software, the state-of-the-art software from Danish Hydraulic Institute and the probable consequences has been presented.

Keywords: SLR, IPCC, MIKE 21, Scenario, Climate Change

INTRODUCTION

It is already established fact that Earth's climate is changing, a major component of which has resulted from anthropogenic causes due to human activities. Because of burning of fossil fuels, deforestation etc. huge increase in Carbon dioxide level in atmosphere from last century till now has become a major concern and the cause of Global Warming. Sea Level Rise globally is contributed from thermal expansion of ocean water and Sea Level Rise for obvious reasons is likely to cause serious impacts on coasts. The coastal changes due to Sea Level Changes also vary depending upon the Coastal Geometry, variation in Hydrodynamic factors, wind, wave, sedimentation patterns and bed soil parameters. Serious concerns on the impact of the rise at important cities like London, New York, Miami, Florida, Tokyo, Shanghai, Mumbai, Lagos, Ho-chi-min City etc. have been highlighted in literature during last few decades. It is stated that a global rise of sea level exceeding 1 m is a plausible scenario for the 21st century and if the melting of Greenland and/or Antarctic ice sheets continue to be significant sources of sea level rise in new high-end scenario there can be up to 2-m rise by 2100 [1].

*Author for Correspondence
Chakraborty Sudipta
E-mail: diptasu@gmail.com

[1]Research Scholar, Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India
[2]Associate Professor, Civil Engineering, Sardar Patel College of Engineering, Mumbai University, Maharashtra, India
[3]Head of Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India

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The impact on economic damage due to sea-level rise was studied for 136 major coastal cities by comparing the expected damage and risk calculation, for two scenarios i.e. One under the

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assumption of no adaptation and the other one in high-end scenario due to additional ice-sheet melting.. In both scenarios Guangzhou (in China) tops the list and next to Mumbai is New Orleans (in Louisiana, USA) which will face the highest risks. Mumbai is at second-most so far as risk is considered. Mumbai has the 2nd highest risk of inundation as found in the analysis [2]. However, thorough research on Sea Level Rise and prediction of the situation in the coming few decades at Mumbai coast is not found in plenty. In this paper the authors attempted to calculate the Sea Level Rise at Mumbai as an impact of climate change till 2050 by utilizing the Climate change tool of MIKE 21 software FM HD Model developed by Danish Hydraulic Institute. There is a high degree of uncertainty in assessing the extent of resultant future sea-level rise which broadly depends on the potential mass loss of the ice-sheets [2].

Because of two reasons (i) ice sheets as well as glaciers in Greenland and Antarctic is melting faster this century than they did and (ii) ocean is becoming hotter and expanding than before as more than 90% of the excess heat trapped by greenhouse gases is absorbed by oceans. It is recognized that Climate change is recognized as the biggest challenge the planet is going to face and reiterated that the major parameters associated with Climate Change and Extreme weather are changes in Temperature and rainfall [3].

Study Area

The study was conducted at Gateway of India with Lat/Long: 18.9220°N, 72.8347°E (Figure 1), where the highest & lowest tide recorded nearby are in the order of magnitude of +3.47 m & (-) 2.95 m above and below Mean Sea Level respectively.

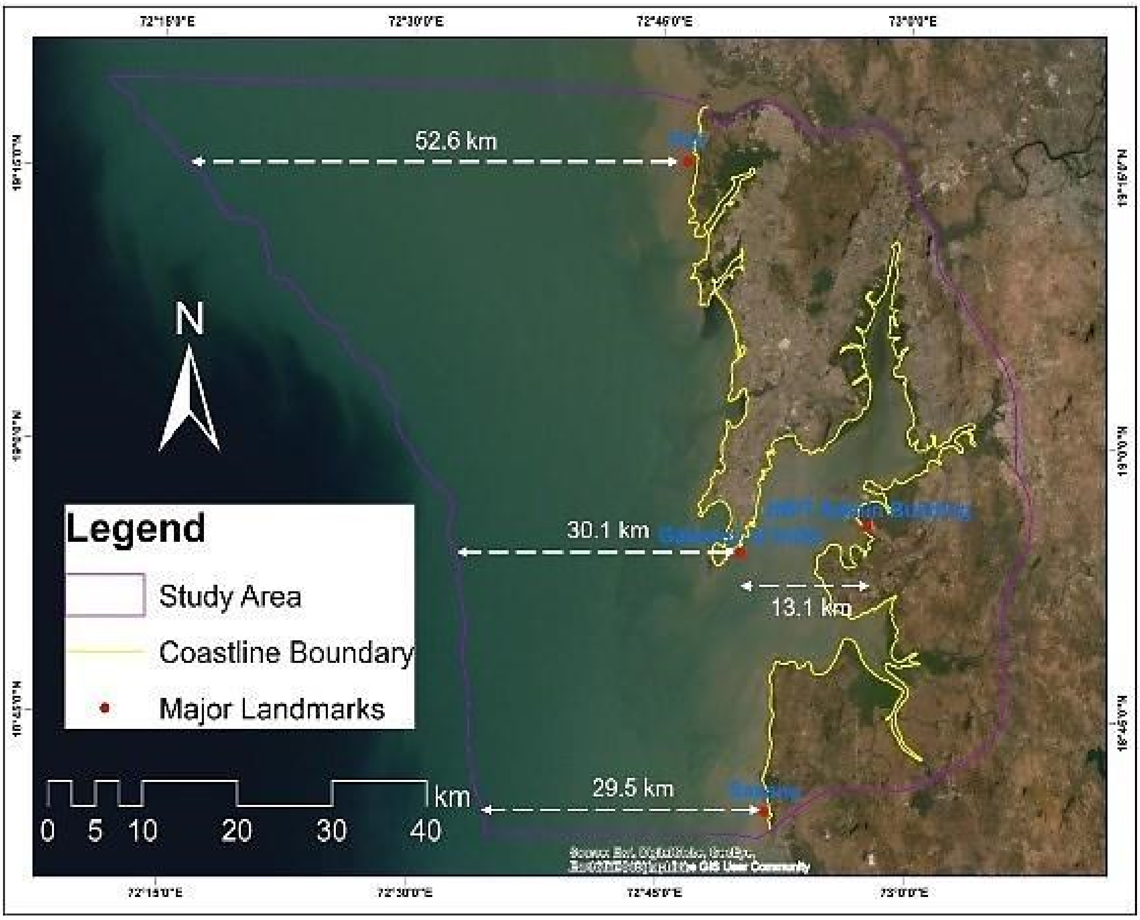

Figure 1. Location Plan-Area of Study.

MIKE 21

The existing setup data is given as input and the MIKE climate change scenario tool for a particular year modifies time series of (i) precipitation, (ii) temperature and (iii) potential evapotranspiration considering the delta change factor with average values for time spans of 20 years, on the basis of selected GCMs and emission scenario [4]. Per emission scenario in each grid point the data sets consists of 12 monthly values (precipitation, air temperature and anomalies) up to 4 sets (different projection years) which are spatially and temporally varied function of the projected year. The MIKE software is equipped with any GCM and emission scenario which considers variables like air temperature, precipitation and potential evapotranspiration. The process of calculation with basic features of Hydrodynamic (HD) model is presented below.

MIKE21 HD

The flow module of MIKE 21 Hydrodynamic (HD) stands upon the depth-integrated incompressible Reynolds averaged Navier-Stokes's equations which is founded on the numerical solution of the two-dimensional (2-D) shallow water equations. Numerical modelling is a widely applied technique and powerful tool to tackle complex problems by computational simulation. All modelling works have been performed using DHI's MIKE21 Flexible Mesh (FM) Flow model numerical model.

Governing Equations

In estuaries, bays and coastal areas the simulation of water levels and flows are done by a general numerical modelling system under the HD module in Mike21. The unsteady 2D flows in vertically homogeneous fluids are simulated with integration of the conservation of mass and momentum over the water column. Flow and water level variations are described by the following relationships:

The continuity is given by: $\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial p}{\partial y} = 0$

The momentum equation in the x-direction is given by: $\frac{\partial p}{\partial t} + \frac{\partial \frac{p^2}{h}}{\partial x} + \frac{\partial \frac{qp}{h}}{\partial y} = -gh\frac{\partial \eta}{\partial x} - k\frac{\sqrt{p^2+q^2}}{h^2}p + \frac{1}{\rho_w}\frac{\partial \mathrm{ht_{xx}}}{\partial \mathrm{x}} + \frac{1}{\rho_w}\frac{\partial \mathrm{ht_{xy}}}{\partial \mathrm{y}} + fq + \frac{\rho_a}{\rho_w}C_w W W_x - \frac{h}{\rho_w}\frac{\partial p_a}{\partial x}$. The momentum equation in the y-direction is given by: $\frac{\partial q}{\partial t} + \frac{\partial p/h}{\partial x} + \frac{\partial q^2/h}{\partial y} = -gh\frac{\partial \eta}{\partial x} - k\frac{\sqrt{p^2+q^2}}{h^2}q + \frac{1}{\rho_w}\frac{\partial \mathrm{ht_{yy}}}{\partial \mathrm{y}} + \frac{1}{\rho_w}\frac{\partial \mathrm{ht_{xy}}}{\partial \mathrm{y}} - fp + \frac{\rho_a}{\rho_w}C_w W W_y - \frac{h}{\rho_w}\frac{\partial \mathrm{p_a}}{\partial \mathrm{y}}$.

where p and q (m^3/s/m) are discharges per unit width in x-and y-directions, respectively, t (s) is time, x and y (m) are Cartesian coordinates, h (m) is water depth, g (9.81 m/s^2) acceleration due to gravity, Ƞ (m) is the sea surface elevation, k is a friction parameter, ρw and ρa (kg/m^3) are the air and water density, respectively, W (m/s) is wind speed, f (1/s) is the Coriolis parameter, τ is the shear stress component (kg/m/s^2) and pa (kg/m/s^2) is atmospheric pressure.

CW = 0.0008+0.000065W is the applied wind friction factor,

Mike 21 FM HD uses the Alternating Direction Implicit Technique to integrate the above equations in the space and time domain. Double Sweep Algorithm resolves the resulting equation matrices for each direction and each grid line. For the shallow water areas, the bed friction is an essential parameter in Mike 21, which is expressed as a function of the Manning number as: $k = \frac{g}{M^2 h^{1/3}}$; where M (m1/3/s) stands for Manning number in numerical hydraulics. In the governing equations, the friction parameter is expressed as Manning's M number (M = 1/n, with n = Manning's roughness coefficient). In the present study, the spatially uniform bed resistance value of M = 32 m1/3/s is considered, the value of which remains in the range of 20–40 m1/3/s.

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For setting up the Mike21 FM HD model the data comprised the following:

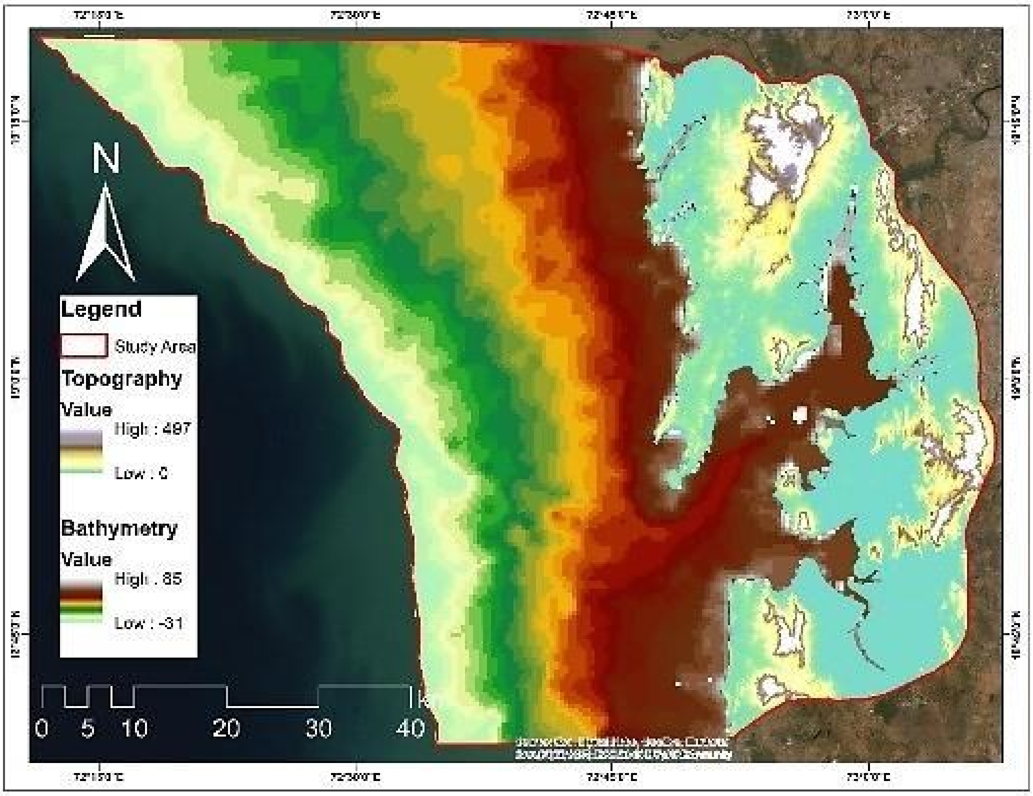
- Mesh file: to provide information on flexible mesh, bathymetry, and boundary locations within the model domain.
- Water levels, velocity or flux values are the boundary conditions, contributing towards energy drive in the model and
- Wind and its effects, which provides a surface boundary condition on wind driven currents and within the model.

Topographic Data and Bathymetric Data is taken from Shuttle Radar Topography Mission (SRTM) 30 m Digital Elevation Model (DEM) and General Bathymetric Chart of the Oceans (GEBCO) respectively. The elevation varies from-31 to 85 m with respect to MSL in the study area. Bathymetric and topographic data were compiled into a consistent database with a horizontal datum of lat/long (WGS84 geographic coordinate system) and a vertical datum of Mean Sea Level (MSL) in support of model construction. Coastline boundary provides a land boundary to the model boundary. Moreover, coastline boundary is required to improve the accuracy of key coastal processes, land-ocean interactions, and the bathymetry effects. The final mesh has around 9207 nodes and 16902 elements. The elements size varies between 3808 m^2 and 8232285 m^2. In the current study, the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) coastline was used.

The MIKE21 hydrodynamic model is governed by the Reynolds-Averaged Navier-Stokes (RANS) equations, which are depth-integrated over the water column (Figure 2).

MIKE & Climate Change

The existing CO_2 emission scenarios considered in the Fourth Assessment Report (AR4) of the Intergovernmental Panel for Climate Change (IPCC) [Meehl et al. 2007] and three other publications on global sea level rise (Horton et al. 2008; Grinsted et al. 2009; Vermeer and Rahmstorf, 2009) shapes the basis of The MIKE Climate Change tool [5].



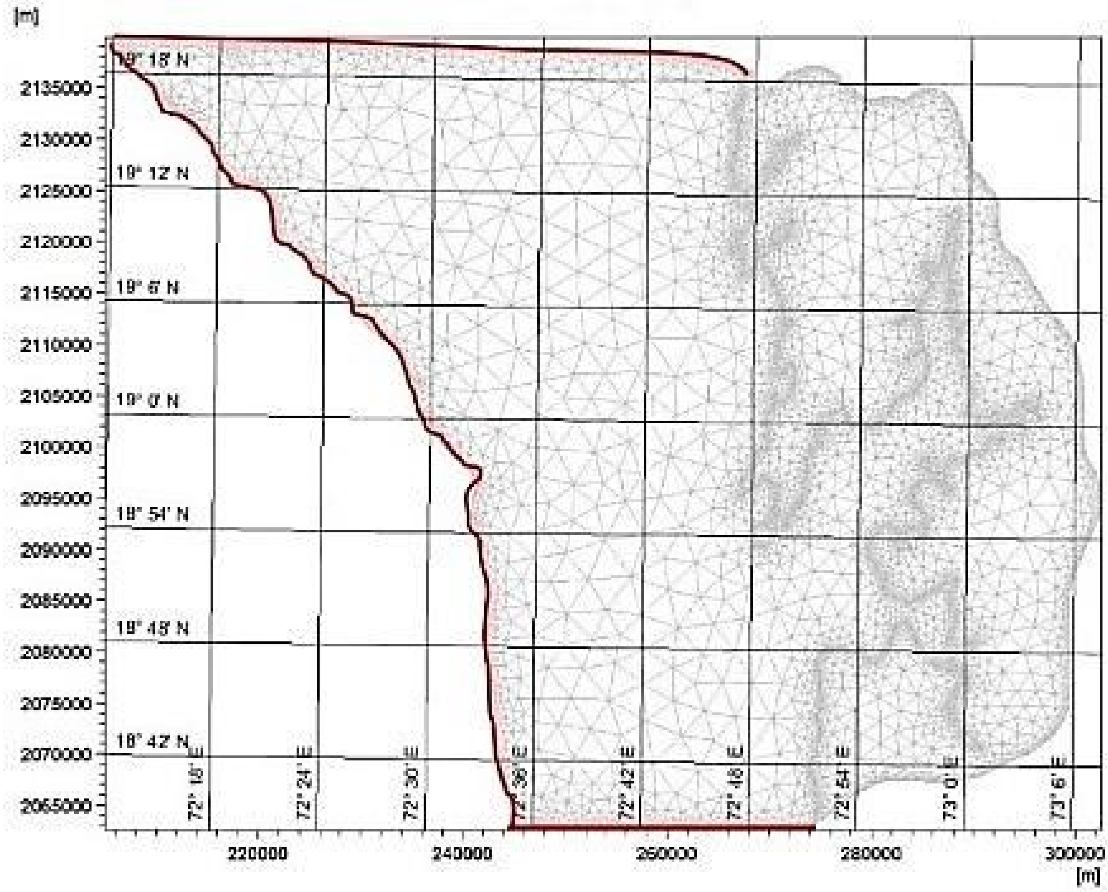


Figure 2. Combined map of topography and bathymetry data; Mesh with Boundary.

Only projected sea level rise for 2050 was generated using the MIKE climate change tool considering base level at 2020.

The most common three scenarios from the Emission Scenarios of the IPCC for surface warming i.e. A2, A1B (RCP6.0) and B1(RCP4.5); from multi-model global averages are included in the MIKE climate change tool. The global greenhouse gas emissions are considered to develop global circulation models for projecting possible future climate change In this study, to generate sea level rise only IPCC AR4's projection for all three emission scenarios for 2050 are required to processed through MIKE 21 FM HD's Climate Change tool to find Sea Level Rise, generate inundation and its areal extend for the study area. However, the sea level rise as projected by software considering the simulation based on Manning's coefficient and the particular applied boundary condition over a period from 2020 to 2050 is to be adopted.

The relation between parameters of respective scenarios viz. Emission, Concentrations and Temperature Projections from AR4 (SRES based) and AR5 (RCP based) alongwith the SLR obtained from IPCC and other three methods inbuilt within MIKE are presented below in Figure 3.

ANALYSIS OF RESULTS

Meehl et al. suggested a model in IPCC AR4 by balancing the main components of sea level rise i.e., between thermal volumetric expansion of water and ice melting. The estimated sea level rise came around 18–59 cm by 2100 through this suggestion in IPCC AR4, whereas when large ice sheets started melting more rapidly than predicted by such models, the estimates no longer remained reliable [5].

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Sl. No.	Emission Scenarios	Specifications	Global Mean Warming^0 C 2046-2065 #
1	SRA1B	Very rapid economic growth of world, maximum population growth during half century and after that decreasing trend, and rapid modern and effective technology growth	1.75
2	SRA2	Rapid world population growth, heterogeneous economics in direction of regional conditions throughout the world	1.65
3	SRB1	Population convergence throughout the worldwith the same global population as in the SRA1B, rapid changes in economic structure (pollutant reduction and introduction to clean and efficient technology resources)	1.29

* Reference Global Climate Projections Chapter 10Table 10.5 IPCC AR4 [75]

Figure 3. (a) Scenario vs. Temperature.

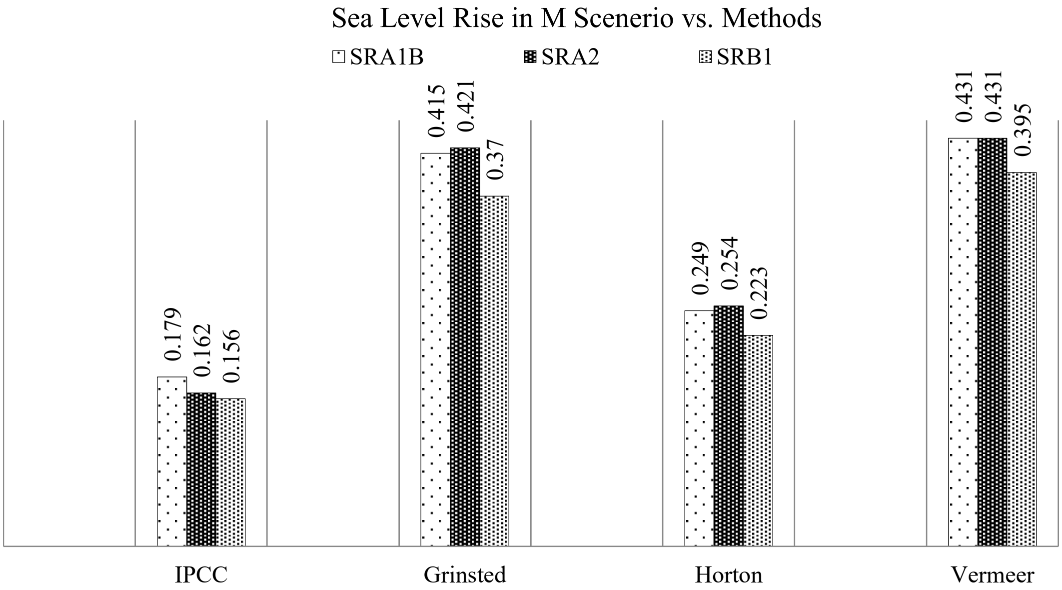

Figure 3. (b) SLR Obtained in M from 4 methods.

A four-parameter linear response equation was developed by Grinsted et al. (2009) with an objective to relate 2000 years of global temperatures and sea level. Monte Carlo inversion was used to estimate the likelihood of distributions of equation parameters allowing visualization of past and future sea level scenarios. When calibrated for past i.e., pre-1990 period, the model reportedly has good predictive power. The high rates of sea level rise could also be validated against from the satellite altimetry. The established relationship between temperature and sea level from 200 to 2100 AD was assumed to project the future Sea level using Intergovernmental Panel on Climate Change (IPCC) temperature scenarios. Multi-proxy reconstructions were assumed for past sea level. For the A1B scenario Sea level 2090–2099 was projected to be 0.9 to 1.3 m [6].

The IPCC AR4 report have been widely debated for the sea level projections. Horton et al. opined that ice sheet discharges accelerations in Greenland and Antarctica could not be explained by ice sheet models and that the IPCC AR4 projections underestimated the sea level rise [7]. Using semi-empirical methods that relate temperature or other climate variables with global see level change various studies

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have been conducted post IPCC AR4 sea level rise projection. Vermeer et al. adopted a simple relationship between global sea-level of decades to centuries to global mean temperature applicable for the past millennium till the next century. The relationship projected a sea-level rise ranging from 75 to 190 cm as per Intergovernmental Panel on Climate Change's Fourth Assessment Report, for the period 1990–2100 [8].

Sea Level Rise [2020–2050]

The MIKE21 FM HD model's climate change tool was run to find the Sea Level Change in 2050 to generate inundation and its areal extend for the study area. The coordinate of Gateway of India under the given Boundary condition was taken as input for the given Climate Change Scenarios under IPCCAR4 and Grinsted 2009 i.e., for SRA1B, SRA2, and SRB1 CO_2 emission scenarios for 2050.

The results obtained from the IPCC and other three methods are presented in the scatter diagram below. The simulated value obtained from IPCC and Grinsted's method are presented below in Figure 4.

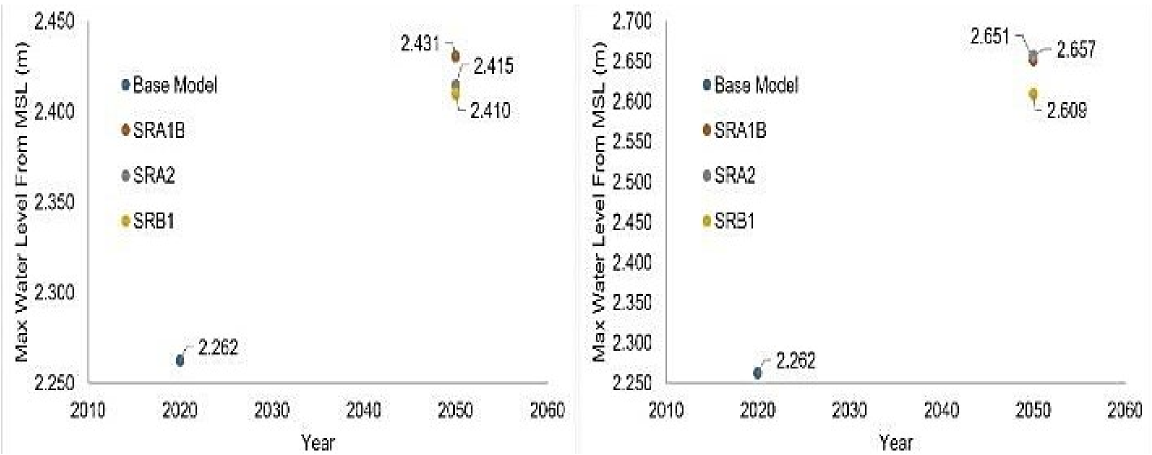

Figure 4. (a) SLR Data-Scenario Vs Methods.

Temp°C	1.75	1.65	1.29
Scenario	SRA1B	SRA2	SRB1
Method	Sea Level Rise Due to Climate Change		
IPCC AR4	0.169	0.153	0.148
Grinsted2009	0.389	0.395	0.347

Figure 4. (b) Sea Water level at the Gateway of India in 2050 considering IPCC AR4 method and Grinsted 2009.

It is extremely difficult to ascertain which particular scenario will be in vogue at Mumbai in 2050. In 2019, a study projected that relative to the level in 2000, sea level will rise 30 centimetres by 2050 in low emission scenario and 69 centimetres by 2100. In the event of high emission scenario, Sea Level Rise will be 34 cm and 111 cm by 2050 & 2100 respectively. In the context of total SLR projections, including contributions from ocean thermal expansion, glaciers, and land-water storage, as per expert judgements, the 2050 L projections were within 16–49 cm range, whereas the 2050 H projections extends up to 61 cm. There is a probability that the rise will be even beyond 2 metres by 2100 in the high emission scenario [9]. The greatest uncertainty lies on how much the ice is going to melt and that too how fast it may. There are repeated warnings on the issue from different corners and moreover there is large fluctuation in the figures upto what level globally the sea can rise. The projected sea level rise till 2100 globally has been apprehended as 1.3 m to 1.9 m in various literature [5, 11, 10].

For the purpose of this study the assumption of sea level rise should neither be pessimistic not very optimistic, however has to be a reasonable one. In the said perspective of uncertainties, choosing any particular becomes a prerogative of subjective assessment. India’s existing target under the Paris Agreement is “2°C-compatible”, as it is within the range of what is considered to be a “2°C compatible” fair share of global effort, even if the country’s total emissions are allowed to increase. From the perspective of Paris Agreement Compatibility, the temperature rise at Mumbai can be reasonably considered well below 2°C but not much above 1.5°C, and from social entitlement be in A2 scenario which aims for regional development. As such based on the above explanations, under Temperature rise of 1.65°C in SRA2 scenario Grinsted's method is considered to suit.

Amongst the two methods i.e., IPCC AR4 and Grinsted's one, the highest value of maximum water level under scenario A2 is 2.657 m above mean sea level. Maximum water level in original or base model (in 2020) was 2.262 m (Figure 5). The Software after further simulation and adopted a Sea Level Rise of 0.395 m. Together with the same from IPCC AR4, the result from Grinsted et al.'s 2009 method [6] is hence implemented for the purpose of comparison. Although the absolute rise varies from 0.156 m to 0.431 m in different methods, these values cannot be linearly added to find the Sea Level Rise as the relation is not linear, instead it depends on many factors such as boundary conditions, terrain elevation and Manning's coefficient.

Sea Level Rise from other factors

Relative Sea Level Rise projections for a specific location take into account the different contributions from the components at the global, regional and local scales, as relevant to the study area.

The components are then added as ΔRSL = ΔSLG + ΔSLRM + ΔSLRG + ΔSLVLM [9], where:

- ΔRSL stands for the change in relative sea level
- ΔSLG stands for the change in global mean sea level = 0.395 m
- ΔSLRM stands for the regional variation in sea level from the global mean due to meteo-oceanographic factors
- ΔSLRG stands for the sea level's regional variation due to changes in the earth’s gravitational field
- ΔSLVLM is the sea level change from vertical movement of land

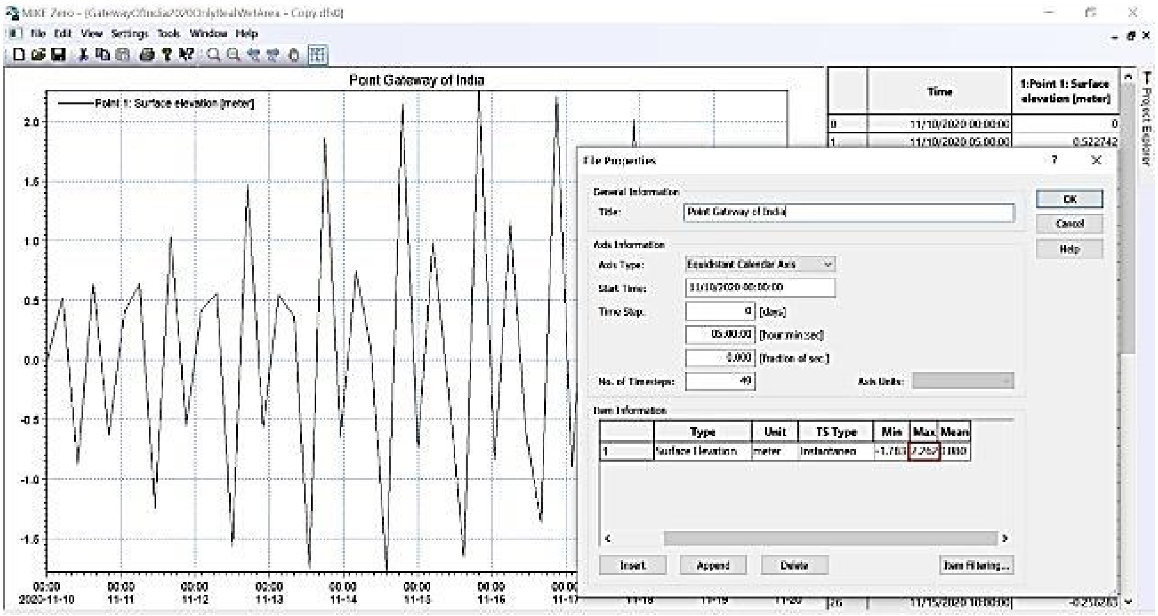

Figure 5. (a) Base Sea Water Level at Gateway of India 2020.

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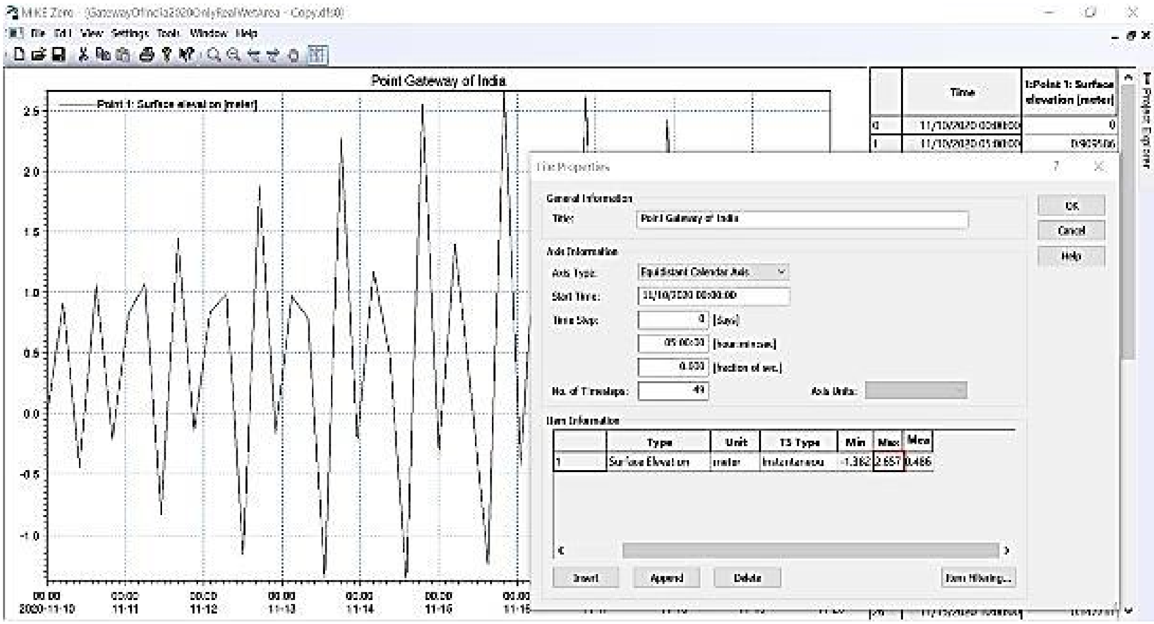

Figure 5. (b) Raised Sea Water Level at Gateway Of India 2050.

DISCUSSIONS

Sea level rises due to contribution of total land ice in 21st century remains highly uncertain and difficult to be quantified. A linear interpolation may be done to assume the SLR at Mumbai on 2050 as per IPCC AR considering 1 m global sea level rise in 2100 [11].

According to McKinsey India sources Mumbai will see a 25 per cent increase in the intensity of flash floods and a 0.5 metre rise in sea level (*Indian Express February 28, 2020*). This is as per comparison between the condition in 2050 for coastal cities like Ho Chi Minh, Florida and Mumbai. Hence as obtained from the simulation done in MIKE the rise of the global mean sea level as an impact of Climate change only may be considered as 0.395 m. In absence of data for ΔSL_{RM} & ΔSL_{RG}; the value of ΔSL_{VLM} (the change in sea level due to vertical land movement from 2020 to 2050) is considered 0.200 mm approximately which when added the Sea Level Rise at Mumbai in 2050 is estimated in the order of magnitude of 0.595 m, excluding the effect of wind and surges.

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Instability of Ice Mass Balance and Climate Change Induced Sea Level Rise-An Appraisal

Chakraborty Sudipta, A. R. Kambekar & Sarma Arnab

The Assam Royal Global University, Guwahati, India

ABSTRACT

It is found from literature on impact of changes in climate and the resultant rise in sea level, that the scenarios, which are presumed for estimating the rise in Sea Level are stranded on a lot of doubts. Projections by different teams of scientists and real time data from IPCC's predictions do not always match and mostly rather differ. Various models so far considered, grounded on mathematical and statistical methods are anticipated to experience unforeseen variation due to the present unpredictable behaviour of the ice sheets. Studies about the contribution from Antarctica itself towards rise in Sea Level predicts abrupt variations in different projections and accordingly the importance of detailed study on Marine Ice Instability has been highlighted in this paper. The phenomenon related to MISI and MICI has been stressed upon to arrive at more correct projections on Sea Level Rise in coming decades and centuries.

Keywords: global warming, sea level rise, melting of ice, ice sheet, ice cliff, uncertainty, instability.

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Instability of Ice Mass Balance and Climate Change Induced Sea Level Rise-An Appraisal

Chakraborty Sudipta[α], A. R. Kambekar[α] & Sarma Arnab[ρ]

ABSTRACT

It is found from literature on impact of changes in climate and the resultant rise in sea level, that the scenarios, which are presumed for estimating the rise in Sea Level are stranded on a lot of doubts. Projections by different teams of scientists and real time data from IPCC's predictions do not always match and mostly rather differ. Various models so far considered, grounded on mathematical and statistical methods are anticipated to experience unforeseen variation due to the present unpredictable behaviour of the ice sheets. Studies about the contribution from Antarctica itself towards rise in Sea Level predicts abrupt variations in different projections and accordingly the importance of detailed study on Marine Ice Instability has been highlighted in this paper. The phenomenon related to MISI and MICI has been stressed upon to arrive at more correct projections on Sea Level Rise in coming decades and centuries.

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Author α: Chakraborty Sudipta, Research Scholar, Department of Civil Engg., The Assam Royal Global University , Guwahati , India.
e-mail: diptasu@gmail.com
α: Kambekar A.R. Dr., Department of Civil Engg., Sardar Patel College of Engineering, Mumbai University, Andheri (W), Mumbai- 400058, India.
ρ: Sarma Arnab Dr., Prof., Head , Department of Civil Engg., The Assam Royal Global University, Guwahati, Assam-781035, India.

I. INTRODUCTION

One of the most important effects of anthropogenic warming in our globe is Rise in Sea Level, which appears as a major challenge to the Civilization as all coastal places with human habitation are likely to face catastrophic inundation threatening migration, health and economic challenges around the world. Due to the complex nature of interactions within seas, troposphere, ice and land, profound doubts remain about the resultant rise in sea level arising out of changes in climate. Scale of longstanding GMSL rise for coming centuries is essential to be known for effective planning of adaptation and mitigation pathways and policies.

II. BACKGROUND

It is highlighted in IPCC's AR-VI (2021), that the global rise in temperature would reach 1.5°C in the 2030s, then again will increase to 1.6°C, and then show a downward trend with temperatures dropping back down to 1.4°C at the top of the century. The Agreement at Paris (2015) resolved the necessity of keeping warming in our globe below 2° C than pre-industrial levels by 2100, with an attempt to restrict the rise within 1.5°C by 2050 or before. However, as per Glasgow Climate Summit (2021), in the next two decades our planet is irrevocably heading towards warming by 1.5° C over preindustrial times. As per existing declarations by countries the globe is now in the direction of 2.7°C minimum rise in temperature by 2100. If this scenario doesn't change globally the rise in sea level will linger much after this century also [1]. From review of some papers presented below it's found that there are plenty of doubts in realistic estimation of Rise in Sea Level.

III. LITERATURE REVIEW

Parris et al. (2012) found various possibilities in imminent rise of GMSL by 2100, up to a high-end of 2.0 m with a low-end of 0.2 m with two optimized intermediate high and low position

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from 1.2 m to 0.5 m (Figure 1).It is stated that the low scenario represents the inferred trend in rise of GMSL adding an additional amount of about 5 cm over the rise in last century, while the high scenario represents another model under more extreme land-ice contributions with an upper limit of GMSL rise. The midway situations signify the upper-end predictions for rise as per IPCC AR4-B1 scenario (Intermediate-Low), and more than a few semi-empirical revisions (Intermediate-High) [2].

Bamber and Aspinall (2013) attempted to ascertain a consensus amongst numerous experts and presumed an unchanging rate of likely rise in sea level, by 2100. They considered the above pre-industrial temperatures up to an increase of 3.5°C, matching with a medium range scenario for emissions of carbon. The average proportion of rise in the seawater level was considered to be 5.4 mm per year by 2100, just only from the Antarctic and Greenland ice sheets, as agreed upon by these experts. After merging the consequences of molten ice and glaciers, along with that from expansion of ocean due to warming, the average estimation for rise in sea level by 2100 was predicted by them to be within the range of 33 to 132 cm. Although they did not rule out the uncertainty on this guesstimate, it was stated to be the best estimate, according to them [3].

Golledge et. al. (2015) observed that the runaway ice loss from Antarctica will cross a tipping point prior to 2100, pledging the planet to have a rise in sea level up to 2 m by 2100 and 15 m by 2300 [4]. Whereas the currents in the top 100 m of the ocean's surface are driven by winds, they stated that currents flowing thousands of meters below surface are driven by thermohaline circulation. This happens due to differences in the water's density, temperature (thermo) and salinity (haline) and inter hemispheric atmospheric cooling at local level is triggered due to reduction of temperature in the bottom water level at Antarctic [4].

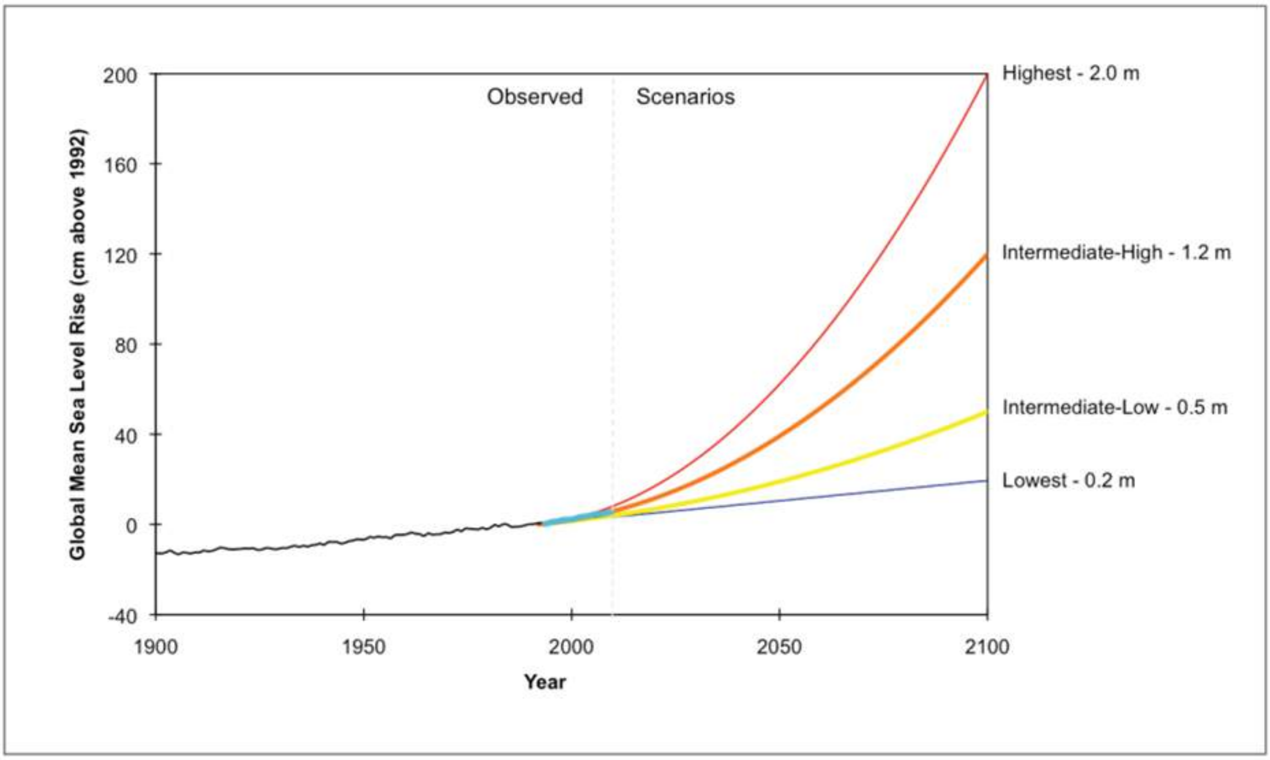

Figure 1: The rise scenarios in Global mean sea level. Source: NOAA - 2012 [2]

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Pollard et al. (2015) explained that as per physical characteristics, the subaerial ice cliffs are prone to collapse due to their self-weight when the height of the cliff exceeds 90 meters. Such instability called MICI (Marine Ice Cliff Instability) leads to failure of ice-cliffs and retreat of ice sheets [5].

Landerer, F. W et. al (2015) revealed that Sea-level rise is accelerating, but the future rate is uncertain. Acceleration is mostly due to increased thermal expansion of the top two kilometers of the oceans which amplified melting of icebergs. A large portion of Antarctica below sea level is subject to melting from below, due to warm water. It causes the ice sheet to peel off the ocean floor, accelerating the flow of the glacier towards the sea. According to reports from the satellite named-GRACE (Gravity Recovery and Climate Experiment), the melting of Antarctica has fast-tracked by a factor of five in recent decades. Uncertainty in forecasting Sea level rises from Antarctica is emphasized [6].

J. Hansen et.al. (2016) highlighted a layer of the cold meltwater at the ocean's surface layer which acts like a lid and facilitates ice melting by increasing subsurface ocean warming. The layer of lid with low-density detains the warming below especially at ice shelf grounding lines where a restraining force develops which limits discharge of the ice sheet [7].

David Docquier (2016) pointed out that warm water at the base of ice shelves (basal) increases the melting, which in turn pushes back the grounding line and the resultant thinned ice-shelves exert less buttressing effect which causes perturbation to Ice sheet and disturbs the stability [8].

Sweet et.al. (2017) on scrutiny of several peer-reviewed publications came out with a physically plausible rise in GMSL due to instability of Antarctic ice-sheet itself within 2.0 m to 2.7 m. The values considered by Paris et al. [2] were revised and they recommended an upper-bound "extreme" scenario for rise in GMSL up to 2.5 m (0.5 m higher) by the year 2100 [9].

Garner et al. (2018) found projections of SLR vacillates and somewhat are usually found more than IPCC's projections. Windows for upper projection regarding SLR predictions are not same across various studies, in reality projections persist to remain ambiguous. According to them a gap in scientific knowledge related to assessing the probable rise in seawater level is evident as per the widely varying results obtained from different studies [10].

Andrew Shepherd et. al. (2018) from the IMBIE team, an international collaboration of scientists known as 'Ice-sheet Mass-Balance Inter-Comparison Exercise' investigated the Antarctic Ice-Sheet and its balance of mass. Regarding the processes responsible for active loss of the AIS, they found absence of proper technical explanations existed till the recent AR5 estimates, Subsequently the integration of the concept of instabilities particularly regarding numerical models for ice sheet was in progress. A high-impact scenario (with low-probability) for future sea level rise resulted in IPCC-AR6, where rise in GMSL up to 2 meters (Figure 1) was not ruled out by 2100 [11].

"Dow, Christine F et. al. (2018) explained MISI as one of the main catalysts for breaking and evacuation of the ice-sheets, stuck on sloping beds underneath sea level. Peripheral ice gets removed by ice cliff failure, which exposes taller ice cliffs more unstable and the process continues. Also, MICI can further increase because of surface melt through ponding and hydro fracture [12].

Jonathan L. Bamber (2019), based on the uncertainties of emission and melting ice volume, suggested that the rise in GMSL being up to 145 cm for contribution from Antarctic contribution by 2100 has 5% chances [13].

Horton et. al. (2020) documented that a group of scientists exercised a repeat survey in 2020, which was earlier conducted in 2014 to find projections for future GMSL rise. Relative 1986–2005, a team of 106 experts projected a rise of 0.30–0.65 m by 2100, and 0.54–2.15 m in GMSL by 2300, under RCP2.6.

This same team however, under RCP 8.5, projected a rise of 0.63–1.32 m by 2100, and a rise of 1.67–5.61 m by 2300 in GMSL. The

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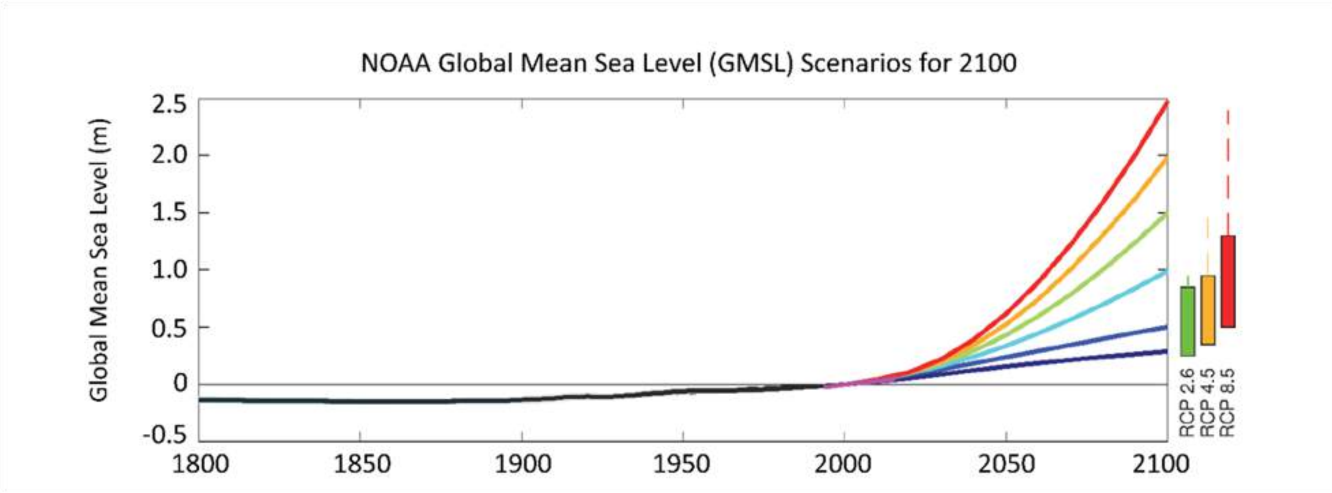

Figure 2: Scenarios for 2100 regarding rise in GMSL (6 coloured lines) [9]

projections for 2100 by these experts in 2020 remained similar with that obtained during the survey in 2014, whereas the projection for 2300 was more than that found in 2014. The experts projected that under the scenario of higher-emissions the rise in GMSL will cross the upper range estimated by IPCC AR5 (0.98 m) and the probability of such exceedance was 42% in the earlier survey (2014) whereas in the recent survey (2020), it was 45%. The cause of such uncertainties in upper-end estimates was diagnosed to be quantum of meltwater from the Antarctic Ice Sheet and its contribution to GMSL from the [14]. Frank Pattyn et al. (2020) had strong positive feedback that Antarctic Ice may yield a larger order of magnitude in Sea Level Rise. How quickly and how plentiful the quantum of melted water will be contributed from Antarctica remains a point of uncertainty. Being its base grounded below sea level on a slope towards inner, the West AIS is stated to have the volume with capacity to raise level of sea by 5.3 m, whereas the East AIS with marine basins has a far greater potential of contribution in rise in sea level up to 52.2 m [15].

Stef Lhermittea et al. (2020) mentioned that the glaciers in Antarctica are changing fast with possible large consequences in global sea level. They also stated that the processes controlling weakening of Ice-sheets and shifting of the contact position at ground is not fully clear. It was indicated by them that 'Thwaites Glacier' also known as 'Doomsday Glacier' will certainly contribute 65 cm. or more to global sea water, if it collapses, which will be sufficient to inundate New York, Shanghai, Miami, Tokyo and Mumbai etc. and will swallow islands like Kiribati, Tuvalu and Maldives. The glacier has already spewed ice into the ocean twice than that in the 1990s. More than 1000 billion tons of ice loss has happened since 2000, the flow speed being doubled in 30 years [16].

Lowry et al (2021) opined that the impact of scenarios of emission on future loss of ice from Antarctic is not expected to arise just within the 21st century. Dynamic ice sheet model simulations under various emissions scenarios of greenhouse gas had overlaps. The period was undis- tinguishable and it was inferred that the impact from the Ice Sheets of Antarctica towards rise of sea level in future is mostly indeterminable. Scientific community requires a focused effort to understand and identify the processes affecting the melting of the Antarctic Ice Sheet (AIS) which is the biggest capacity indefinite supplier to rise in sea level in future. It is indicated that the 21st century's warming situation will control the resulting long-term contribution on sea water- level from the Ice Sheets of Antarctica. It is possible that between the uppermost and lowermost scenarios of emissions in succeeding centuries, there can be multimeter differences in sea level [17].

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Edwards et al. (2021) while projecting rise in sea level from the contributions of ice, showed a widespread variety of predictions for Antarctica's future contribution to rise in GMSL. According to a statistical assessment, relative to the 1995–2014 baseline, out of an overall rise in GMSL up to 62–101 cm, the melt water from ice of Antarctica will add 14–32 cm. Because of inadequate understanding of melting processes, it is seen that the IPCC AR6 projections [6] vary from these projections [18].

DeConto, R.M et al. (2021), recognized the deep uncertainties in probabilistic projections in sea level with contributions from Antarctica further to the middle of the 21st century after the Paris Agreement. For the SSP 5–8.5 scenario, when MICI and MISI are accounted for, a higher estimate in rise amounting to 20–53 cm for GMSL is likely by 2100 from Antarctic's contribution itself. The target set by the Paris agreement regarding emission will be met only if the global emissions trajectory tracks SSP 1–2.6, the lower-emission scenario. In that case ice loss to the ocean from Antarctica and its contribution

to Rise in Sea Level by 2100 is likely to be meaningfully lower i.e., 12–31 cm by 2100 and about 100 cm by 2300 [19].

Chakraborty et al (2021) observed that reports from different groups of scientists and their models have regenerated the ambiguity of uncertainty to a greater extent, although starting from studies through statistical forecast, numerical modeling including actual measurement of rise in sea level from Satellite Altimetry, scientists have taken recourse. There are comments which have either intensified or decreased the rate of the global rise in mean sea level. [20]

Colleoni et al. (2022) pointed out that as melting ice sheets do not lead to uniform Sea level Rises all over the globe, this further confounds understanding the niche contributions from Antarctic itself. Due to rearrangement of ocean water due to flow of melt ice into the ocean, the gravitational field and rotational state of Earth changes. Land also rises due to exertion of less pressure on the land below by the remaining ice. It is suggested that substantial loss of ice from Antarctica can be barred only by restricting emissions of greenhouse gasses within RCP 2.6 scenario. It was also opined that emissions in the coming decades will largely impact the quantity of melt water from the ice sheets of Antarctica for raising sea water level globally. In Higher-emission scenarios by the year 2300, ice loss from Antarctica is likely to contribute to an increase of sea level by 0.6–3 meters [21].

II. MARINE ICE INSTABILITY

4.1 Marine Ice Sheet Instability

A sheet of ice supported on the sea bed level is a marine ice sheet. Seawater being denser than ice, marine ice sheets can only remain stable when the mass of the ice sheet exceeds the mass of the seawater displaced by the ice (Archimedes' principle) and the ice below water level remains in place by the load of ice over it. The thinning of ice (due to melting) when it reaches a threshold value, the ice below water floats and warm water enters below it. After basal melting [8], thinning of the ice shelf decreases the buttressing effect supporting the interior grounded ice. Pollard et al. (2015) [5] and David Docquier (2016) [8] opined that in such conditions the retreat of Ice sheets gets accelerated. The grounding line shifts and such resultant retreat of the ice sheet was first termed as MISI or Marine Ice Sheet Instability by Mercer, J. H. (1978) [22]. Due to warming when surface meltwater increases, hydro fracture takes place causing ice-shelf calving and meltwater drainage into crevasses goes on. This hypothesis of Marine Ice Sheet Instability considers that due to warming in ocean melting of ice increases, particularly when the ice rests on a reverse slope gradient (from coast towards interior of marine sheet) due to lesser buttressing force from inside the ice and shifting of the grounding line controls the stability of ice sheet [25].

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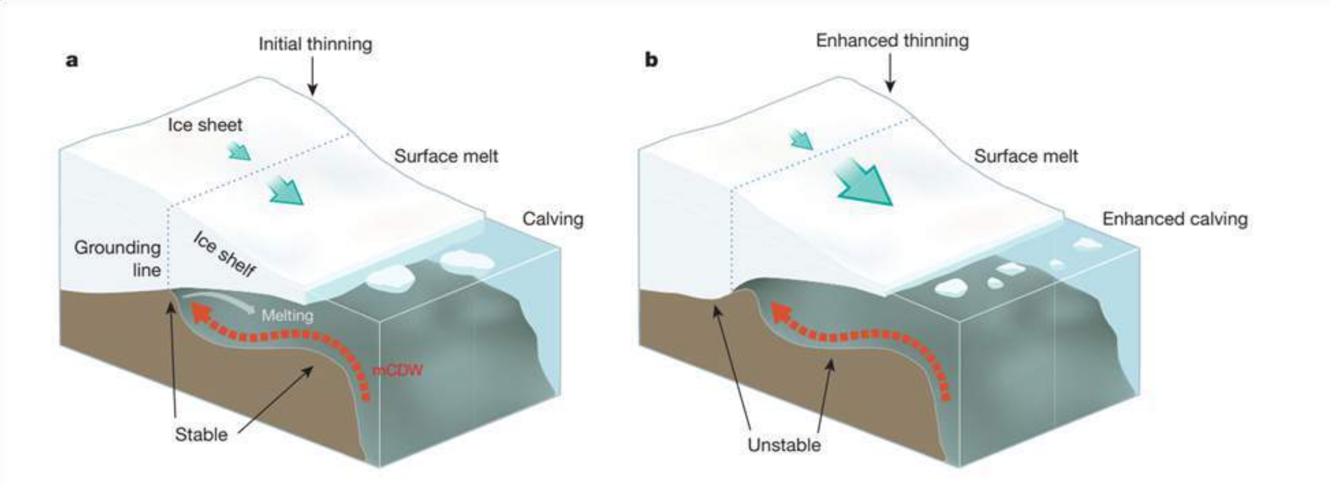

Figure 3: Schematic representation of MISI with (a) an initial stable grounding-line position and (b) an unstable grounding-line after the incursion of warm modified Circumpolar Deep Water (mCDW) [26]

Figure 4 shows the schematic representation of the phenomenon. When the ice at the grounding line is in upper position then the upstream grounding line retreats which stops only after a new stable position is reached. When the bedrock slopes down from the coast towards the interior of the marine ice sheet, the grounding line is not stable (in the absence of back forces provided by ice shelves). The position and migration of this grounding line control the stability of a marine ice sheet. Historically, blame for the sudden breakdown of the Larsen B ice shelf at Antarctica2002) into the ocean has been given to this mechanism by Vaughan et al. (2008) as summers (preceded the event [23].

4.2 Marine Ice Cliff Instability

The section of ice exposed to the ocean or air above the waterline which actually becomes the calving face is known as the ice cliff. The formative and conceptual differences between Ice Sheet and Ice Cliffs are shown in the pictures in Figure 5. When the increasingly tall unstable ice cliffs are exposed due to reduction of buttressing effect at the bottom, the cliff collapses. When the strains ("stretching" forces) inside ice cliffs longitudinally are too large for it to sustain, the taller subaerial vertical cliff along the ice margins turns out to be structurally more unstable, which triggers catastrophic failure of the cliff into deep basins. The combined effect of surface melt, shifting of the grounding line as well as hydrofracturing is known as MICI [Marine Ice Cliff Instability]. Helsinki Discrete Element Model popularly known as 'HiDEM' is a particle model which is used for determining the fracture and resultant calving of retreating marine glaciers by simulation of the elastic behaviour through Finite Element Analysis. Such parameterization [27] assists for critical representation for retreat via ice-cliff failure in models. If certain conditions are met and ice-cliff height increases with each failure occurrence, the ice-cliff failure process can become self-sustaining. It is observed that glacier-retreat rates rise non-linearly with ice-cliff height. Figure 6 shows the schematic representation of MICI and the collapse of the ice cliff.

V. CONCLUSION

Question remains whether Antarctica will empty itself into the ocean or as a cascading effect pull the adjacent ices also, which eventually may contribute towards a few meters of rise in sea-level. Satellite altimetry reports have already shown signs of fast depletion of ice. Prediction of the sea level rise by mid-century or top of it, happens to be an extremely complex task, which other than global warming in fact also basically depends on both MISI & MICI. Mercer, J. H. (1978) predicted these as a threat to disaster [22] and Vaughan, David G. (2008) reiterated the potential for ice destabilization in a runaway fashion which will contribute to comparatively faster rise in sea level [23]. Scientists are sure

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about the acceleration of Rise in Sea Level in future decades and centuries. Currently there are limitations in our understanding in ice flow and sliding, with historical constrained iterative statistical ice sheet simulations. It is confirmed that under high- emissions scenarios, contribution towards sea water level from the Antarctic Ice Sheet will not be the same from low-emission scenarios for centuries. It is seen that there are plenty of concepts regarding scenarios and innumerable number of papers exist in literature with historical data and stochastically obtained projections regarding Sea Level Rise. There is no shortcut to save our planet from Sea Level Rise. With concerted effort, different nations have already started planning for reduction of burning fossil fuel, go for reducing emissions and thereby try to limit the warming.

Marine Ice Sheet (Source: Science.org)

Marine Ice Cliff (Source :SciTechDaily.com)

Figure 4: Marine Ice Sheet & Marine Ice Cliff

It may be said without hesitation that ironically the climate has started behaving erratically and the civilisation is heading towards catastrophe. In established cold countries, occasions of very high temperature are unprecedentedly seen to occur, whereas unexpected snowfall is found occurring intermittently even at the desert countries. Extreme weather events, storms are happening more frequently than expected.

On random review of the papers in the last decade it is observed that the expected global sea level rise till 2100 or beyond on account of global warming may lie in a range of say 25 cm to as high as 2.5 to 3 m or even more, which mainly will depend on Instability phenomenon of Marine Ice viz. MISI and or MICI. In this paper the authors intend to stress upon continuous elaborate studies on Instability phenomenon of Marine Ice as already highlighted by Chii Yun Tsai et.al. (2020); stating that improved knowledge about the interactions between climate scenario and ice sheets and also how ice sheets would react to future changes and variability in climate are extremely important for vigorously guesstimating the influence of AIS to SLR [24]. It is opined that even if the increase of temperature be kept under control as per Paris Agreement and Glasgow Summit, a severe uncertainty remains on how fast and how much the Icebergs will seriously melt, which can lead to a disaster in our world.

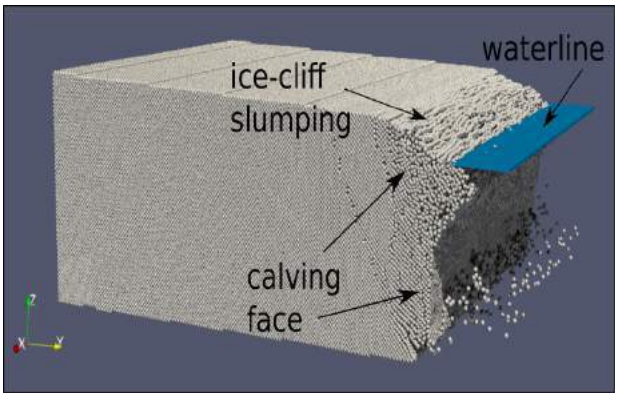

Figure 5: Schematic representation of collapse of an ice-cliff [27]

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Impact of Sea Level Rise due to Climate Change and Anticipated Consequence of Slamming Forces on Deck Elevation of Port Structures- An Assessment

Chakraborty Sudipta[1,*], Kambekar A.R[2], Sarma Arnab[3]

Abstract

The research methodologies on climate change, particularly the deterministic factors have undergone gradual changes during last few decades in respective IPCC's Assessment Reports. The original concept of emission scenarios (2000) was reconsidered as socio-economic scenarios till AR4, later appraised as Representative Concentration Pathways till AR5 based on Radiative Forcing, the capacity of a gas affecting the change in energy (trajectories not emissions) in the atmosphere. Lately in AR6 the criterion is assessed in terms of Shared Socioeconomic Pathways (SSPs) and scenarios projected up to 2100. The resultant sea level rise also has undergone multiple changes in their forecast, especially due to the uncertain and fast changes in the dynamics of melting of ice-sheets. This paper calls for evaluation of impact of sea level rise on critical infrastructure in Ports and Harbours in view of the fingerprint of uncontrolled and rapid increasing of melting of ice. The criticalities on marine structures have been reviewed and the concern is emphasized.

Keywords: Global warming, sea level rise, waves, slamming forces

INTRODUCTION

It is already a known fact that due to impact of climate change sea level is rising continuously and by now there is a prominent fingerprint of the Sea Level Rise. Similar to its effect on the shifting of coastline, anticipated inundation and related disaster in coastal cities, the ports and the maritime structures inside ports and harbours will also be subjected to unsolicited forces developed from the waves during extreme weather events and the design of port structure calls for a review from both operation and stability point of view. It is apparent that climate change induced sea level rise is likely to influence the damage to marine structures due to possible extent of inundation. Sea Level Rise due to climate change and frequent extreme weather events both call for reviewing the status of the structures in the port, particularly those constructed for a deep-drafted vessel away from the shore. The stability of the port structure like jetty or berth largely involves wave/structure interaction. Different kinds of Maritime structures including those which are built offshore say for example offshore jetty, offshore jacket platforms or say breakwaters are subjected to breaking waves as well as non-breaking waves sometimes which may be time dependent i.e., "pulsating" type of loads. Structures in shallow water are subjected to loads from breaking waves or broken waves. In case of vertical wave structures

***Author for Correspondence**
Chakraborty Sudipta
E-mail: diptasu@gmail.com

[1]Research Scholar, Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India
[2]Associate Professor, Civil Engineering, Sardar Patel College of Engineering, Mumbai University, Maharashtra, India
[3]Head of Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India

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loads from waves may therefore be more vehement. Coastal flooding and overtopping is expected to increase when level of sea level will rise. Such risk is likely to be amplified due to impacts of high temperature because of global warming. For obvious reasons ports will be vulnerable to damage as these marine infrastructure are located either along the coast or low-lying deltas or estuarine areas. The hazards apprehended to develop during effect of climate change, like surging of waves, winds, effects of flooding etc. This paper intends to summarize some of the important aspects, which needs special attention and the related changes in the port structures envisaged till 2050.

LITERATURE REVIEW

There can be various implications of climate related extremes on ports in terms of their structural stability and functionality. Some of the pertinent parameters have been taken from various literatures to identify the measures required to strengthen port structures like jetties based on structural parameters and dynamic loading due to waves including wind.

According to Bea et al. (1999) [1] wave-in-deck loading, because of its complexity in nature demands a thorough analysis, which essentially comes out as an extended version of Morison's equation where the total wave-in-deck force (F_{tw}) on a platform deck is given by:

$$F_{tw} = F_s + F_d + F_l + F_i + F_b$$

Where, the components are: slamming (F_s), drag (F_d); lift (F_l), inertia (F_i) and buoyancy forces (F_b).

Tirindelli et al. (2003) [2] describes Wave-in-deck loads as a combination of (i) horizonal wave loads (ii) uplift load on decks (iii) wave uplift force on structural elements and fenders (iv) downward suction loads on decks after inundation (Figure 1).

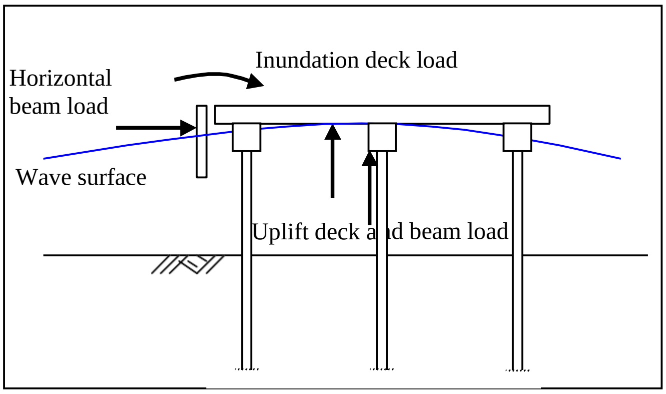

Figure 1. Wave-in-deck loads [2].

Slangen et al. (2014) [3] ignored all inundation upto a height of 0.5 metres while assessing damage of critical infrastructures for ports. In their modelling for simulation of inundation they hypothesized that coastal structures will not be vulnerable to collapse. The changes in population density and the related estimated damage to various coastal expansion scenario was studied to arrive at the required strengthening of such structures.

Loads on Berthing Structures was elaborated by Chopra et al. (2015) [4] as: Dead Load, Live Load, Wind Force, Seismic Force, Active Earth Pressure, Berthing Force, Mooring Force, Hydrostatic and Hydrodynamic Forces, Force due to drag Application of Forces, Temperature Force, Current forces etc. The kinetic energy E imparted to a fender system by a vessel moving with velocity V is given by

$$E = \frac{W_D \times V^2}{2g} \times C_m \times C_e \times C_s$$

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Where, E = Berthing Energy (Tm), W_D = Displacement Tonnage (T), V = Velocity of Berthing Vessel in m/sec, Cm, Ce, Cs stands for Mass Coefficient, Eccentricity Co-efficient, Softness Co-efficient respectively and g is Gravitational Acceleration (m/sec^2).

Bellad et al. (2018) [5] elaborated Non-Breaking Wave Load, Water Current Loads and Wave Slam Load on port structures as follows.

i. Wave slamming is the striking action of rising wave crests onto the elevated cross head of marine structure due to which both lateral and vertical loads are exerted on the supporting structure. This is a reason in marine structure the decks, cross heads or beams of the structure are raised above highest high tide level in order to avoid the hit of wave slam forces at sides and upward thrust on soffit of deck slab.
ii. Wave slam (dependent on height of wave crest and still water level) induces highest wave moment in piles among all wave loads and current loads. The base moment is high due to increase in lever arm length between slam forces exerted at the top of cross head/deck/beam to pile bottom fixity level.
iii. Wave slam force exerted on the soffit of pile caps and cross beams will result in uplift force which induces tension forces in the piles affected.

McLeod et al. (2018) [6] explained that though ports are usually designed for extreme probabilities (for a return period of 1 in 100 years), consequence of climate change i.e., expected increase in frequency and intensity of extreme weather events and sea-level rise raises concern to designers.

Hanson et al. (2020) [7] summarized what's Ports expect from the Climate Policy in 2050, wherein the effects, impacts and consequences of climate change on the ports have been discussed.

Izaguirre et al. (2021) [8] studied risk vulnerability of 2,013 ports worldwide under high-end global warming scenario considering the hazards from atmospheric as well as marine aspects comparing with the established thresholds.

Xiang et al. (2021) [9] used Lagrangian-Eulerian numerical method for developing a 3D hydrodynamic model for assessment of impact of solitary wave on open-girder decks. Parametric investigation reveals that the Number of Girders (Ng) of a superstructure has a complex role on deck geometries. With increase of Ng the horizontal and uplift forces increases for small wave heights, whereas the opposite happens for large waves. Eddies are formed in each chamber when Ng is large which create multiple but weaker impacts on the deck due to dissipation of energy. The total loads from waves are split into slamming and quasi-static components which indicates formulation of predictive load equations. The wave usually cannot inundate the whole deck width which means that inundation and related forces are dependent on the wavelength.

Chakraborty et al. (2021) [10] identifies two reasons (i) ice sheets as well as glaciers in Greenland and Antarctic is melting faster this century than earlier and (ii) ocean is becoming hotter and expanding than before as more than 90% of the excess heat trapped by greenhouse gases is absorbed by oceans.

Coulson et al. (2022) [11] found that the fingerprint of melting near the Greenland Ice Sheet can be detected using ice mass loss estimates made from radar altimetry and model reconstructions of nearby glaciers. Rapid melting of ice sheets and glaciers raises the global average sea level but does so in a complex pattern of regional increases and decreases called a sea level fingerprint.

To assess the impact of future climatic and socioeconomic conditions on coastal flooding Koks et al. (2022) [12] have expressed a storyline framework referring to multiple historic events. The historic storm events viz. Xaver (northern-German coastline), Xynthia (French coastline) and a storm surge event (coast of Emilia Romagna at Italy) were referred.

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DISCUSSION

It reveals from above that wave-in-deck loads occurs at three phases: (i) when the wave crest touches the soffit of the deck a high magnitude impulsive force but with short duration, (ii) a pulsating (slowly-varying) positive force follows this phase and then by (iii) if the deck is inundated a pulsating negative force. It can be fairly noted that dynamic impulsive forces for a short duration causes severe stress and may lead to damage, failure out of fatigue and yields may occur locally. The magnitude of such forces can be much more than maximum pulsating forces. The Impulsive loads even if confined in small area for short duration is also very vital for individual members locally than from the total structure. Propagation of a wave under the platform continuously creates outshooting jets at the wave front which impacts the structure. The laterally outshooting jets disappear as soon as the free water surface alongside the platform rises up along the soffit level. A difference in elevation develops between the fluid beneath the platform and that alongside the platform. At this stage pulsating positive force (uplift) generates. Various studies reveal that this kind of force is governed by vertical distance from the bottom of the deck and the sea water level i.e., the wave height (or wave crest elevation) and clearance above the still water level. When later the free surface of the undisturbed wave eventually falls below the soffit level, as a result the free surface underneath the platform moves inward and the contact area between the platform and the wave reduces. The wave height and width of platform and the clearance governs the pulsating (suction) force acting under the platform. Later if the wave consistently inundates the deck, the negative load, weight of the water above the deck comes into effect. This together with the suction force generates a downward load significantly, sometimes which may be of the same magnitude with that of the pulsating positive uplift force. The structure obviously becomes vulnerable to a serious loading condition and is a matter of concern for the structural engineers. Researchers suggest stable and consistent relations with dimensionless forces and parametric study of wave-induced forces jetties exposed to such random forces [13].

CONCLUSION

By now it is undeniable fact that Climate change is recognized as the biggest challenge the planet is going to face and the major parameters associated with Climate Change and Extreme weather are changes in Temperature and rainfall out of which eventually sea level rise is one factor of concern. It is felt that design considerations should be revised well beforehand to escape from the possible catastrophes. The present provision for Deck Elevation Clause 6.3.7 of IS 4651 Part- V 1980 states: QUOTE "The required deck elevation of cargo terminal is related to optimum position of the cargo transfer equipment to cater to two extreme situations, that is, with the largest vessel in light displacement condition at high water and with the smallest vessel fully laden at low water. The deck elevation should normally be at or above highest high- water spring plus half height of an incident wave at the berth location plus a clearance of 1 m" UNQUOTE. To combat with the slamming force generating out of Sea Level rise, the clause no 6.3.7 in IS 4651 (Part V) warrants attention, which may have to be revisited/changed. Additional provision for free board in future design of Jetties/Other Marine Structure in Mumbai region during 2050 and beyond is envisaged . In this paper the authors express their concern on revision of codal provisions to cater to the forces discussed above.

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Research JoOST

Calculation of Element Stiffness Matrix for Finite Element Analysis of Pile Dynamic Stability

Arnab Sarma[1,*], Sudipta Chakraborty[2], A.R. Kambekar[3]

Abstract

To analyze the dynamic stability of pile structures under periodic loads, we have employed the finite element method in this study. The soil modulus was assumed to vary linearly. We have formulated the Mathieu-Hill eigenvalue equation to analyze the stability and instability regions for different static and dynamic load factors. Our research provides valuable insights into the behavior of pile structures when subjected to dynamic loading. The findings can be utilized to design more stable and dependable structures, ultimately contributing to the development of a safer and more resilient built environment.

Keywords: Mathieu-Hill eigenvalue equation, dynamic stability analysis, pile structures, periodic loads, linear soil modulus, stability regions, instability regions, static load factors, dynamic load factors

INTRODUCTION

In the field of practical engineering applications, the stability and instability of offshore structures, especially piles, are of utmost importance. Parametric vibrations with significant amplitudes of oscillation can occur in these structures due to the periodic axial and lateral forces that they are often subjected to. Numerous previous studies, including those by Bolotin [1], Beliaev [2], and Mettler [3], have extensively documented the stability of structures under pulsating periodic loads with axial forces. For structures with simply supported boundary conditions, stability and instability regions exist for lateral motion, and the governing equation is of the Mathieu-Hill type. The Mathieu-Hill equation can be obtained through Galerkin's method or integral equations for structures with arbitrary support conditions. Previous research has investigated the dynamic stability of a uniform bar with various boundary conditions using the Finite Element Method, as well as the stability of piles subjected to lateral loads. Studies have also been conducted on the parametric instability of a uniform column using a discrete element numerical approach. The most recent publications on the stability behavior of structural elements have been provided by Abbas and Thomas [1, 2, 4–6].

Analysis

The equation governing the free vibration of an axially loaded discretized system [7], with the neglect of rotary and longitudinal inertia, is represented as

$$[M]\{\ddot{q}\}+[Ke]\{q\}-[S]\{q\}=0 \tag{1}$$

Here, {q} refers to the generalized coordinate, [M] is the mass matrix, [Ke] represents the elastic stiffness matrix, and [S] denotes the stability matrix, which is a function of the axial load. The equation governing the behavior of a pile under lateral load can be expressed as follows.

$$\frac{d^2}{dx^2}\left(EI\frac{d^2y}{dx^2}\right)=-E_s y \tag{2}$$

The lateral deflection, y, of a pile at any point x along its length is influenced by both the flexural

***Author for Correspondence**
Arnab Sarma
E-mail: arnab.sarma@rgi.edu.in

[1]Head of Civil Engineering Department, The Assam Royal Global University, Guwahati, Assam, India
[2]Research Scholar Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India
[3]Asociate Professor, Department of Civil Engineering, SPCE, University of Mumbai, Maharashtra, India

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rigidity, EI, and soil modulus, Es. While an analytical solution for y is available for piles with constant flexural rigidity and soil modulus with depth, it provides limited design data like Moment and Shear. In reality, the soil modulus and flexural rigidity may vary with depth, making it challenging to obtain an analytical solution for the lateral deflection of piles. Additionally, the soil modulus, Es, can be non-linear and dependent on both the pile deflection, y, and soil behavior. In the case where the variation of Es is linear, such as (C1 + C2 x), even a single instance can lead to a complex analytical solution. As a result, numerical approaches like the finite difference or finite element method are necessary. When a system is exposed to periodic force, predicting its behavior becomes even more challenging, necessitating sophisticated techniques for accurate forecasts. The governing equation is transformed to the form $[M]\{q^{\circ\circ}\}+([Ke] - \alpha P^*[Ss] - \beta P^* Cos\Omega t[St])\{q\} = 0$, where $P(t) = Po+Pt \cos \Omega t$, and Ω represents the disturbing frequency. One way to represent the static and time-dependent components of the load is to express them as a fraction of the fundamental static buckling load P. This load is the critical compressive load at which a structure will buckle under a purely static load. By expressing the static and time-dependent loads as a fraction of P, it is possible to evaluate the stability of a structure and predict its behavior under different loading conditions. This approach is commonly used in structural analysis and design to ensure that a structure can withstand anticipated loads without failure. Here, α and β denote percentages of static and buckling load P*, respectively [7–11].

$$[M]\{q^{\cdot\cdot}\}+([Ke] - \alpha P^*[S_s] - \beta P^* Cos\Omega t[S_t])\{q\} = 0 \tag{3}$$

The matrices [Ss] and [St] are responsible for accounting for the effects of Po and Pt, respectively. The resulting equation represents a second-order differential equation system with periodic coefficients of Mathieu-Hill type. The stable and unstable regions can be distinguished by identifying the boundaries through periodic solutions of period T and 2T, where T is equal to $2\pi/\Omega$. These periodic solutions play a crucial role in determining the stability and instability regions for a given system. In other words, the stability boundaries are determined by finding the values of load parameters for which the system exhibits periodic solutions, while the instability regions correspond to load parameters for which the system exhibits unbounded responses [3, 12, 13]. If the static and time-dependent components of loads are applied in a time-dependent manner [Ss] and [St] are set to [S], allowing for the identification of boundaries for the regions of dynamic instability [8] using the following equation:

$$\left[[Ke] - \left(\alpha \pm \tfrac{1}{2}\beta\right)P^*[S] - \frac{\Omega^2}{4}[M]\right]\left\{q\right\} = 0 \tag{4}$$

The combination of the two conditions in Equation (4) results in two sets of Eigen values that define the regions of instability. To determine the zones of dynamic stability, the disturbing frequency is denoted by Ω, where $\Omega=(\Omega/\omega_1)\,\omega_1$ and ω_1 represents the fundamental natural frequency obtained from solving Equation (5). Equation (4) can be applied to solve several related problems, including free vibration with no static axial load (i.e., when $\alpha = 0$, $\beta = 0$, and $\lambda = \omega 1/2$), vibration with static axial load (i.e., when $\beta = 0$ and $\lambda= \Omega/2$), static stability with no vibration (i.e. $\alpha = 1$, $\beta = 0$, and $\Omega = 0$). To determine the matrices [Ke], [S], and [M] for a pile, the fundamental natural frequency and the critical static buckling load must be solved from Equations (5) and (7), respectively. The resulting stability equation can be used to identify the boundary between stable and unstable regions for both static and dynamic loading scenarios. The stability regions can be determined based on periodic solutions of period T and 2T, where $T = 2\pi/\Omega$, with stable regions occurring when $\alpha = 1$, $\beta = 0$, and $\Omega = 0$, and dynamic stability occurring when all terms are present. However, in practical scenarios, the soil modulus and flexural rigidity may vary with depth, which may require additional analytical solutions to accurately predict the behavior of the pile. Once these values are known, it is possible to solve for the regions of dynamic stability using Equation (4):

1. *Free Vibration* with $\alpha = 0$, $\beta = 0$, $\lambda = \omega_1/2$ the natural frequency,

$$[[Ke] - \lambda^2[M]]\{q\}= 0 \tag{5}$$

2. *Vibration with static axial load*: $\beta = 0$, $\lambda= \Omega/2$

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$$[[Ke]\ \alpha P\ ^*[S] - \lambda^2\ [M]]\{q\} = 0 \tag{6}$$

3. *Static stability* with $\alpha = 1$, $\beta = 0$ and $\Omega = 0$

$$[[\ Ke] - P\ ^*[S]]\{q\} = 0 \tag{7}$$

4. *Dynamic stability* when all terms are present.

To solve the problem, we need to generate the stiffness matrix [Ke], the stress matrix [S], and the mass matrix [M] for the pile. The fundamental natural frequency and the critical static buckling load of a pile can be obtained by solving Equations (5) and (7). These values are essential for determining the regions of dynamic stability using Equation (4). To generate the matrices [Ke], [S], and [M] for the pile, the fundamental natural frequency and the critical static buckling load must be calculated first.

Element Stiffness and Mass Matrices

The pile is divided into several finite elements, with each element having two nodes (i and j) and three degrees of freedom: axial and lateral displacement (u and v) and rotation ($\theta = dv/dx$) for each node. The nodal degrees of freedom for the Finite Element Model of the structure correspond to axial and lateral force (P and Y) and moment (M). The displacement function for the element, as shown in Figure 1, is used to determine the nodal displacement vector. $\{q_e\} = [x_i\ y_i\ \theta_i\ x_j\ y_j\ \theta_j]^T$

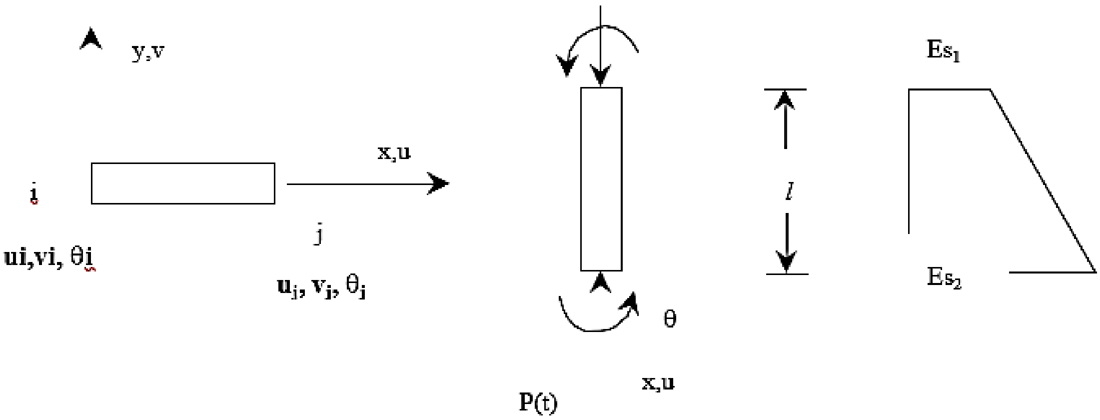

Figure 1. Typical pile element.

The corresponding elemental force vector is obtained by multiplying the transpose of the elemental stiffness matrix [K] with the nodal displacement vector. Thus, the elemental force vector [F] can be expressed as $[K]^T*[u]$.

$$\{F_e\} = [P_i\ Y_i\ M_i\ P_j\ Y_j\ M_j]^T.$$

The displacement functions are assumed to be generalized polynomials of the most common form.

$$v(x) = \alpha_1 + \alpha_2\ x + \alpha_3\ x^2 + \alpha_4\ x^3 \text{ or, } \{v(x)\} = [p(x)]\ \{\alpha\}\ldots \tag{8}$$

The no. of terms in the polynomial determines the shape of the displacement model where α-s determine the amplitude.

The generalized displacement models for any element are as follows:

$$u = \alpha_1 + \alpha_2\ x; \quad v = \alpha_3 + \alpha_4\ x + \alpha_5\ x^2 + \alpha_6\ x^3 \quad \& \quad \theta = dv/dx = \alpha_4 + 2\alpha_5\ x + 3\alpha_6\ x^2.$$

Substituting the nodal co-ordinates, the element displacement vector for an element of length "*l*", {q} can be written as

$$\{q\} = [A]\ \{\alpha\} \text{ or, } \{\alpha\} = [A]^{-1}\{q_e\} \tag{9}$$

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Therefore, from Equation (8), $\{v(x)\} = [p(x)]\,[A]^{-1}\{q_e\} = [N(x)]\{q\}$ (10)

where matrix [N(x)] is the element shape function. Assuming polynomial expansions for u and v, the strain energy expression becomes.

$$U = \tfrac{1}{2}EI\int_0^l \left(\frac{d^2v}{dx^2}\right)^2 dx + \tfrac{1}{2}EA\int_0^l \left(\frac{du}{dx}\right)^2 dx \quad - \tfrac{1}{2}P\int_0^l \left(\frac{dv}{dx}\right)^2 dx + \tfrac{1}{2}\int_0^l E_s v^2 dx \tag{11}$$

The strain energy U of an elemental length *l* of a pile subjected to an axial load and lateral load.

$$= U_1 + U_2 + U_3 + U_4.$$

The stiffness matrix $[K]_{U1}$ for bending only is obtained from the first term of U1 as shown in Figure 2(a). Similarly, the stiffness matrix $[K]_{U2}$ for axial deformation is only obtained from the second term U2 as shown in Figure 2(b). Considering the beam-column action for axial load only, the stiffness matrix due to U3 is $[K]_{U3}$ as shown in Figure 2(c). Using Equations (8) and (9), Equation (12) can be simplified, and the stiffness matrix can be evaluated as $[K]_{U4}$, as shown in Figure 2(d).

To obtain the final stiffness matrix $[K]_e$, all four cases are considered, i.e., all four terms of U1, U2, U3, and U4 are involved, and the corresponding stiffness matrices K_{U1}, K_{U2}, K_{U3}, and K_{U4} are superimposed, as shown in Figure 3(a).

$$U_4 = \int_0^l \left[\tfrac{1}{2}E_{S_1}v^2 + \tfrac{1}{2}\left(\frac{E_{S_2} - E_{S_1}}{L}\right)uv^2\right]dx \tag{12}$$

$$\begin{array}{cc} & \begin{array}{cccc} v_1 & \theta_1 & v_1 & \theta_2 \end{array} \\ [K]_{U_1} = & \begin{bmatrix} a & b & -a & b \\ & c & -b & d \\ & & a & -b \\ & & & c \end{bmatrix} \end{array}$$

(for bending only)

$$[K]_{U_2} = \begin{array}{cc} \begin{bmatrix} \frac{AE}{L} & \frac{-AE}{L} \\ \frac{-AE}{L} & \frac{AE}{L} \end{bmatrix} & \begin{array}{c} u_1 \\ u_2 \end{array} \end{array}$$

(for axial load only)

Where a = 12 D, b = 6LD, c = $4L^2D$, d = $2L^2D$ Where $D\underline{\Delta}\frac{EI}{l^3}$

(a) Stiffness Matrix (for bending) (b) Stiffness Matrix (for axial load)

$$[K]_{U_3} = P\begin{bmatrix} \frac{-6}{5L} & \frac{1}{10} & \frac{6}{5L} & \frac{1}{10} \\ & \frac{-2L}{15} & \frac{-1}{10} & \frac{L}{30} \\ & & \frac{-6}{5L} & \frac{-1}{10} \\ & & & \frac{-2L}{15} \end{bmatrix}$$

$$\begin{array}{cc} \begin{array}{c} V_1 \\ \theta 1 \\ V2 \end{array} & [K]_{U_4} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ & & S_{33} & S_{34} \\ & & & S_{44} \end{bmatrix} \end{array}$$

(c) Stiffness Matrix (Beam-Column Action). (d) Stiffness Matrix (All Action).

Figure 2. (a–d) Stiffness matrices.

The expression for kinetic energy for a pile loaded laterally and axially the expression for strain energy is given by,

$$T = \tfrac{1}{2}\int \mu\{u^2 + v^2\}dx = \tfrac{1}{2}\int \rho A\ \{u^2 + v^2\}dx \tag{13}$$

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Where μ = mass per unit length of the pile, ρ is density and A is sectional area, u and v are the axial and transverse displacement. Using expressions for u & v, $T = ½ [q]^T[M]\{q\}$

For axial vibration only: $T = ½ \int \mu u^2 \, dx$ (14)

$$N_1 = \left(1 - \frac{3x^2}{1^2} + \frac{2x^3}{13}\right)$$

$$N_2 = \left(x - \frac{2x^2}{1} + \frac{x^3}{1^2}\right)$$

$$N_3 = \left(\frac{3x^2}{1^2} - \frac{2x^3}{1^3}\right)$$

$$N_4 = \left(-\frac{x^2}{1} + \frac{x^3}{1^2}\right)$$

$$[K]_e = \begin{bmatrix} \frac{AE}{L} & 0 & D \underline{\Delta} \frac{EI}{L^3}\ 0 & \frac{-AE}{L} & 0 & 0 \\ 0 & a - \frac{6}{5L} + S_{11} & b + \frac{1}{10} + S_{12} & 0 & -a + \frac{6}{5L} + S_{13} & b + \frac{1}{10} + S_{14} \\ 0 & 0 & c - \frac{2L}{15} + S_{22} & 0 & -b - \frac{1}{10} + S_{23} & d + \frac{L}{30} + S_{24} \\ 0 & 0 & 0 & \frac{-AE}{L} & 0 & 0 \\ 0 & 0 & 0 & 0 & a - \frac{6}{5L} + S_{33} & -b - \frac{1}{10} + S_{34} \\ 0 & 0 & 0 & 0 & 0 & c - \frac{2L}{15} + S_{44} \end{bmatrix}^P$$

Figure 3. (a) Element stiffness matrix.

$$[M] = \begin{bmatrix} 140M & 0 & 0 & 70M & 0 & 0 \\ 0 & 156M & 22LM & 0 & 54M & -13LM \\ 0 & 22LM & 4L^2M & 0 & 13LM & -3L^2M \\ 70M & 0 & 0 & 140M & 0 & 0 \\ 0 & 54M & 13LM & 0 & 156M & -22LM \\ 0 & -13LM & -3L^2M & 0 & -22LM & 4L^2M \end{bmatrix}$$

Figure 3. (b) Mass matrix.

The displacement model for axial displacement is taken as

$$u = u_1\left(1 - \frac{x}{1}\right) + u_2\left(\frac{x}{1}\right) \quad (15)$$

For bending vibration only: $T = ½ \int \mu v^2 \, dx$ (16)

The displacement model for lateral displacement is given by.

$$v = N_1v_1 + N_2\theta_1 + N_3v_2 + N_4\theta_2 \quad (17)$$

Where N_i i =1,4 are the standard shape functions as derived from Equation (10) as

Where a = 12 D, b = 6LD, c = $4L^2D$, d = $2L^2D$ and S11 – 44 as in $[K]_{U4}$

So, the expression of T. Mass Matrix [M] can be determined as given in Figure 3(b).

$$M = \frac{\rho AL}{420}$$

Analysis of the Whole Problem

The displacement approach is a widely used method to solve the problem, and it involves several key steps. Firstly, the elemental matrices are assembled to form the overall stiffness and mass matrices. Next, the fundamental natural frequency and critical static buckling load are determined from Equation (3) and Equation (6), respectively. The dynamic stability regions can then be calculated using Equation (10).

Boundary conditions are also taken into account, leading to the solution for the nodal displacements through the generalized equilibrium equation. In this problem, it is crucial to obtain the design data,

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including the bending moments and shear force at nodal points. The number of degrees of freedom in the problem is determined by 3n, where n is the number of nodes.

To obtain the expanded element stiffness matrices Ke, the stiffness coefficients are placed in their relevant positions, while the remaining entries are filled with zeros. The overall stiffness matrix, [K], is obtained by combining the element stiffness matrices for all E elements.

$[K] = \sum_{e=1}^{E} [\overline{K}]_e$ The equilibrium equations of the assembly can be represented as $[K]\{\delta\}=\{F\}$. The given displacement conditions are integrated into the equations, and the resulting system of equations is solved to obtain the unknown nodal displacements [10]. To enhance computational efficiency, the symmetry and banded structure of the resulting equations are commonly utilized. After assembling the stiffness and mass matrices, the frequency ratio can be determined by solving the eigenvalue problem stated in Equation (10). $\mathbf{\Omega}/\omega_1$, which provides information about the dynamic stability regions.

CONCLUSION

The regions of instability in the parameter space of (β, Ω/ω_1) can be extended to cover various values of the static load factor, α. This extrapolation allows for faster convergence of the boundary frequencies for the initial few regions of instability. The resulting non-dimensionalized regions exhibit distinct characteristics. After obtaining the lower and upper boundaries of the instability regions, they can be compared with Mathieu's diagram [1] to further analyze the dynamic stability of the system.

4.

Notation :

A	Area of Gross section.	E	Modulus of Elasticity.
[K]	Stiffness Matrix	I	Elemental length
[M]	Mass Matrix	N	Shape Function
P	Axial Periodic load	P *	Fundamental Static Buckling load
{q}	Generalised Co-ordinates	[S]	Stability Matrix
t	Variable time	T	Kinetic Energy
U	Strain Energy		
u	Axial displacement of node	v	Lateral displacement of node
x	Axial co-ordinate	y	Lateral Co-ordinate
α	Static load factor	β	Dynamic load factor
ρ	Density		
ω_1	Fundamental Natural Frequency		
Ω	Disturbing Frequency	μ	Mass per unit length.
P_o, P_t	Time independent amplitudes of load		

S_{11} = 156B + 72C S_{23} = L (13B + 14C)

S_{12} = L (22B + 14C) S_{24} = L^2 (- 3B – 3C)

S_{13} = 54B + 54C S_{33} = 156B + 240C

S_{14} = L (-13B –12C) S_{34} = L (- 22B – 30C)

S_{22} = L^2 (4B + 3C) S_{44} = L^2 (4B + 5C)

Where, B = E_{S1}. L/420 C = $(E_{S2} – E_{S1})$. L/840

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A Contemporary Review on Geo-engineering Techniques for Mitigation of Accelerated Rise in Global Sea Level in the Past Eight Hottest Years

Sudipta Chakraborty [a++*], A. R. Kambekar [b#] Arnab Sarma [a†]

[a] *Department of Civil Engineering, The Assam Royal Global University, Guwahati, India.*
[b] *Department of Civil Engineering, SPCE, University of Mumbai, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Because of extreme heat during the last few years, absorption of heat in ocean water is continuously on the rise and due to additional melt water from icebergs the phenomenon of sea level rise is gradually coming to an alarming level. The present scenario based on the proposed mitigation measures to restrict the rise in temperature hardly commensurate with the decisions in Paris Agreement. Currently although geo-engineering, which is a mechanism to limit extraordinary sea level rise, has attracted scientific interest as per the current state of drastic changes in climate change, standard mitigation measures may not be enough to stop sea-level rise. This paper examines the various approaches. and options under Geo-engineering and compares effectiveness of traditional and modern geo-engineering techniques vis-à-vis other conventional mitigation

[++] *Research Scholar;*
[#] *Associate Professor;*
[†] *Head;*
**Corresponding author: E-mail: schakrabortydc@rgu.ac, diptasu@gmail.com;*

measures. It is opined that conservative and groundbreaking techniques can decrease the ongoing rise in sea-level, however most befitting results would be accomplished through the combination of approaches.

Keywords: Geo-engineering; sea-level rise; aerosol injection; marine cloud brightening; ocean-fertilization.

ABBREVIATIONS

SLR : Sea Level Rise
RCP : Representative Concentration Pathway
SSP : Shared Socioeconomic Pathways
MICI : Marine Ice Cliff Instability
MISI : Marine Ice Sheet Instability
IPCC AR6 : Intergovernmental Panel on Climate Change Assessment Report Six
CMIP6 : Coupled Model Intercomparison Project Phase 6
GHG : Green House Gas
NOAA : National Oceanic and Atmospheric Administration
ENSO : El Niño-Southern Oscillation

1. INTRODUCTION

Because it takes decades to millennia for the limitless deep-sea water and icebergs to adjust to global anthropogenic warming, rise in sea level is a continuing effect of changes in the climate. The quantum of rise in sea level is stated to be exceeding 1 m at the top of the century and if melting of icebergs continues in a high-end scenario there can be rise upto 2 m by 2100 [1]. Due to absorption of 90% of the excess heat trapped by greenhouse gases, ocean is increasingly getting hotter and is expanding. Further, also due to melting of ice in Polar Regions, Sea level rise is accelerating [2].

Circulation of wind within northern and southern hemispheres (Coriolis Effect –Fig. 1) contributes to seasonal variations in climate and the effect of El Niño (the hotter phase) and La Niña (the cooler phase) also influences (Fig. 2) the process. Climate Change is bringing in differences in the average ocean temperatures, winds, surface pressure etc. quite significantly.

In reality, it is quite problematic for the current models to anticipate the future conditions and their impacted SLR distributions. Despite significant uncertainty in accuracy of the climate models' estimates, SLR projections as of now are obviously based on the presently available climate models only. According to simulations of global climate models with transient greenhouse gas fluctuations, the average increase in global surface temperature over the past 30 years has been 0.2°C each decade. The havoc of recent rapid warming shows a rise in temperature above 1°C compared to that in 2000, because of the likelihood of its effects on sea level and species extinction, is considered as "unsafe and risky" changes in the climate [3]. Having risen the temperature above 2°C by 2100 (for scenarios RCP2.6 or equivalent SSP1-2.6) relative to pre-industrial values, the high-end global SLR projections are 0.9 m by 2100 and 2.5 m by 2300 out of ongoing and speculated global warming. Similar estimates are made for high end scenarios (i.e., for RCP8.5/SSP5-8.5), which might raise SLR upto 1.6 m in 2100 and 10.4 m in 2300. Long-term methods for mitigation are necessary, given the significant and expanding gaps between the scenarios beyond 2100.

The process of melting of icebergs, which adds to sea level rise- particularly, how fast these are going to melt and in how much quantity, is highly ambiguous due to low-slung knowledge of the entire procedures. Earlier high-end assessments focused on mechanisms of Instabilities in the Marine Ice Cliffs (MICI) and in the Marine Ice Sheets (MISI) to assess the judgement of ice shelf breakdown. But definitely in past eight hottest years, because of continuous rise of temperature, the melt water has accumulated more than envisaged. Obviously, understanding both, i.e. the melting process and control in emission scenario are equally important to assess the high-end SLR [4].

In the prevailing circumstances of so-called phenomenon of ice dynamics during acceleration in the ongoing warming situation, and prevalent deep ambiguity in socio-political and financial deviations amongst nations, model hierarchy for the complex science of climate change is quite a challenging task. Even in terms of forecast by IPCC AR6, in 2022 the differences in contributive influences in the form of (SSPs) analyzed by latest climate model CMIP6, in reality the predictions are still remaining unreliable. Even then, in a state where all human-caused GHG emissions say if instantly terminated, self-sustaining melting will still occur. Because of the current unpredictable ice sheet dynamics, models that have been built on numerical and probabilistic methodologies are predicted to vary drastically and the acceleration in global warming remains difficult to be ascertained [5].

In the Paris Agreement nations agreed for a worldwide agenda to avert unsafe and risky changes in climate by restricting rise in temperature under 2°C and hunting for attempts to retain the rise within 1.5°C, as well as trying to recuperate the capacity of various nations to handle the effects of changes in climate and aid them in their exertions with appropriate strategies [6]. A review of the ongoing situation reveals that the restriction of rise in temperature does not fully commensurate with the desirable status.

2. THE CURRENT SCENARIO

Global warming impacted Sea Level rise is basically a combination of: Rise of sea level due to (i) Thermosteric i.e., increase in the water level of sea because of volumetric expansion of aquatic mass & (ii) Bary static rise in sea-level i.e. the increase in level of water at sea for addition of water to the sea from other sources (like meltwater from glaciers).

Globally it is recorded that the past eight years have been so far the hottest. Oceans were the warmest on record, with around 58% of their surfaces experiencing a marine heatwave. With the rise in the mean global temperature by 1.15 °C from pre-industrial time, year 2022 was the fifth to sixth warmest year. Globally heat and acidity levels in Ocean have hit record highs and glaciers in Alps in Europe and ice in Antarctica ice touched record low volumes. For the first time in history, none of the snow on Switzerland's glaciers survived the summer season, and the main glaciers that scientists use as a health check for the planet has decreased by more than 1.3 m in just one year [7].

This has happened in spite of the rare third year of La Nina---a natural temporary cooling of parts ofthe Pacific Ocean that changes weather conditions worldwide. According to definitions by NOAA, El Niño and La Niña are opposite phases of a natural climate pattern across the tropical Pacific Ocean that swings back and forth every 3-7 years on average, that can affect weather worldwide. Together, they are called ENSO (pronounced “en-so”), which is short for El Niño-Southern Oscillation.The ENSO pattern in the tropical Pacific can be in one of three states: El Niño, Neutral, or La Niña. El Niño (the warm phase) and La Niña (the cool phase) and contributes to significant changes in the average ocean temperatures, winds, surface pressure, and rainfall. Neutral indicates that conditions are near their long-term average.

3. CONTEMPORARY MITIGATION APPROACHES

The main mitigation strategies being used to combat sea level rise are briefly discussed here, along with any drawbacks they may have.In light of this, major solutions to the problem of contemporary sea level rise have mostly been focused on emissions control and adaptation. In the coming decades, anthropogenic activities will play a significant role in the rise of the oceans. Occurrence of a moderate disturbance or a catastrophic flood depends on how much emissions are constrained and reduced [8]. The finest path of achievement would therefore is to curtail and eliminate greenhouse gas emissions, while combating the rise in sea level rise, which as a matter of fact, is no longer preventable. In order to restrict rise in temperatures globally within 1.5°C above preindustrial period, nations are required to control their peak GHG emissions under the Agreement.

4. EMISSION MITIGATION

It is already agreed and determined decrease in emissions is the predominant best strategy to mitigate long-term sea level rise [9]. Two incredibly distinct futures are conceivable as we look towards the end of the twenty-first century and beyond. If the Paris Agreement's pledges to gradually phase down greenhouse gas emissions are reserved, the rise in the Global Mean Sea Level may be limited within 50 cm. However, if releases keep increasing at the prevailing rate, the sea level might rise by up to 4 m by 2300 and by 1 m by 2100 [8]. Although 197 countries have approved the Agreement since it

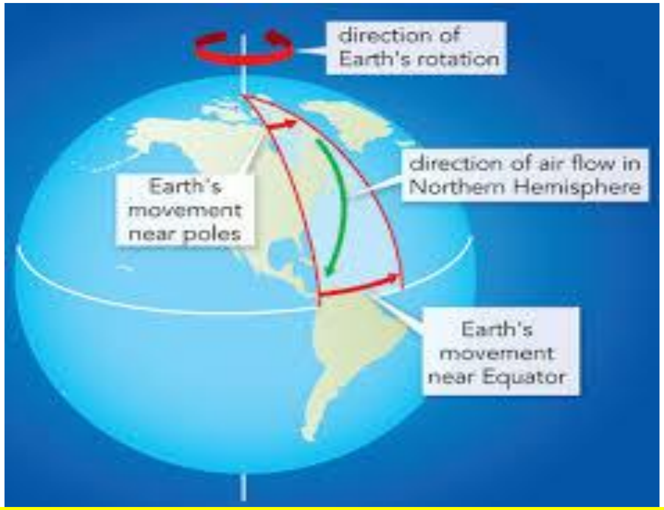

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Fig. 1. Coriolis Effect

Source – Island Physics (Image: Prentice Hall)

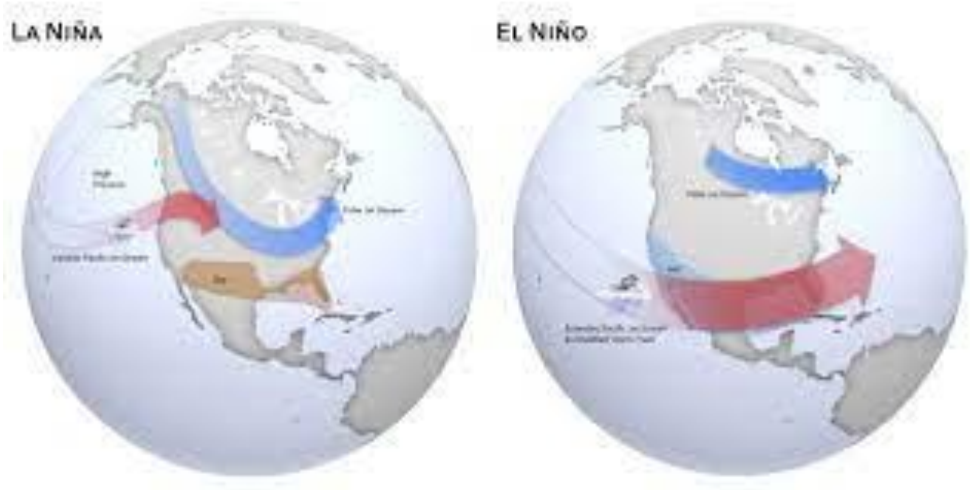

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Fig. 2. El Nino (Warm) & La Nina (Cool)

Source: The National Environmental Education Foundation https://www.neefusa.org/

was established in 2015 and many of them have reaffirmed their commitments since then [10], progress has been uneven [11]. Morocco's emissions are now the only ones that are consistent with the 1.5°C route [6]. Only a small number of nations are 2°C compatible, and the majority of those who [10] nevertheless fall into the inadequate or critically deficient categories, thus impeding efforts to appropriately address fast rise in sea level through restricted paths for mitigation of emissions. Therefore, preventing sea level rise may need more than just reducing emissions; it also necessitates coordinated global action, of which the geo-engineering method is gaining popularity among experts.

5. ADAPTATION MEASURES AGAINST SEA-LEVEL RISE

Protecting coastal areas from floods and water damage is the main goal of current adaptation methods. Traditional defensive strategies, for example erecting sea-walls and levees, creating adaptable structure, or repurposing present structures to be more robust (e.g., elevating and flood-proofing structures) are some of these methods [8]. Numerous communities will weigh the dangers and costs of adjusting with sea's rise in general, leaving those as it is, or attempting to protect coastal structures with multiple defences (Environmental Protection Agency, 2021). Due to additional factors, such as sinking soil, coastal megacities like Jakarta may experience considerable damage from increase of sea level spanning from 20 to 40 cm [8]. Sustaining or repairing natural barriers like adding sand to seashores that have eroded, constructing barrier islands, and restoring wetlands in tidal zones, helps protect coasts along with providing more ecological services [12]. Adaptation techniques are typically implemented locally, in contrast to mitigation of emissions, the ultimate success of which depends on effectiveness of many measures in a collective manner. By 2050, it is predicted worldwide the rise in Global Mean Sea Level on beaches will at least be around 20 to 40 cm [8]. Even while the sea level increase may seem acceptable, regional contributions and other mitigating factors may make it worse in the form of rise in relative sea level, making some areas more severely affected. Whenever it is feasible, adaptation will be a viable option. Despite unlikely emissions reductions, adaptation is also vital to prevent the rise in sea level that has already been locked in.

Particularly in underdeveloped countries, adaptation frequently entails expensive procedures and conflicts with budgetary constraints, which limit a region's capacity to build efficient defences and infrastructure. As a result of the coastal areas being submerged by the sea, fast increasing waves have significant effects on them. A place will have to be abandoned if it cannot afford the expenses of putting protection and adaptation measures in place, which would cause social, economic, and environmental losses [13]. In response, research into newer and more unconventional strategies in slowing rise in sea level has increased over last few decades. One of these strategies is Geo-engineering.

6. GEO-ENGINEERING

For monitoring the current state of climate change, geo-engineering has attracted interest of the scientific community, as a technique to mitigate exceptional sea-level rise, Geo-engineering, often known as climate engineering, is the thoughtful modification of nature's systems to maintain a particular climate [14]. Geo-engineering mostly involves solar geo engineering, which requires atmosphere to be free from carbon dioxide and increasing the albedo from the earth's surface to reflect more sunlight back into space [15]. This has been the focus of research as a wave of specialised methodologies [16] have emerged over the last ten years [6]. Following solidified thinking in this situation, the application of geo-engineering becomes urgently necessary. Before determining how innovative geo-engineering techniques may aid in sea level rise mitigation, it is crucial to first determine why they may be required. In this paper the different aspects of Geo-engineering have been attempted to collate after review.

Geo-engineering approaches are classified according to the three major climatic systems: atmosphere, hydrosphere, and cryosphere (Fig. 3). Furthermore, space-based geoengineering technologies are a powerful tool for mitigating sea-level rise.

The viability of engaging reflective or refracting shields of glass , developing of sun-shades, satellites mounted with mirrors, solar buffers and heat absorbers in space, as well as the option of generating rings of dust around the Earth, analogous to those available around Saturn, are gaining attention. Dependent on position on the Earth, the depth of troposphere varies within a thickness of 5 to 9 miles (8 to 14 km) .The Poles at the northernmost and southernmost point of the earth have the minimum thickness of ice (thinnest). This layer contains the densest layer of air we breathe as well as have maximum clouds in the sky.

Snowflake, sea frost, freshwater and river frost, Icemass, glaciers and frost caps, frost sheets, ice tables, permafrost, and seasonally ice-covered land comprise 'cryosphere'. Etymologically "cryosphere" descends from "kryos," a Greek word which means ice. Above the Terrain's face this zone of stratosphere extends upto around 31 miles (50 kilometers) starting from about 4 to 12 miles (6 to 20 kilometers). This layer contains very little water vapour and about 19% of the atmospheric gases [17]. In this location with altitude the temperature rises.

According to ongoing research, some, if not all, of these strategies could constitute an important tool-kit for climate intervention or a climate barrier [18]. Furthermore, these strategies have the practical advantage of not requiring complex planning at land and also avoids direct changes to the atmosphere. Under the banner of geo-engineering, the following measures are being studied for mitigating global warming:

- **Atmosphere**

i. Injection of Aerosol at Stratosphere [17] = The injection of reflective particles of micro size into the stratosphere for lowering atmospheric temperatures. From now onwards till 2100, injection of aerosol or installation of a mirror system at space can reduce thermic fever with an accelerating rate of 1 W/m2 per decade which inter-alia could control rise in sea levels.

ii. Injection of Aerosol with a radiative forcing decrease of 4 W/m2 may well interrupt rise in sea-level rise in coming 40-80 years. Injection of Aerosol seems to fail in benefit of cost analysis without indefinite sustainability and the harm produced by the macroclimate reaction to the misters is lower than 0.6% of the global world product [19].

iii. Brightening of Marine Cloud [20] = The microparticle infusion into maritime stratocumulus clouds in order to increase reflectivity and thereby counterbalance the warming in atmosphere.

iv. Brightening of Cirrus Cloud [21] = Silver iodine injection into cirrus clouds can weaken or else eradicate the clouds and allows exit of long-wave warm air fallout from troposphere.

v. Microbubbles [22] = Injection of Surfactant on the surface of ocean can improve albedo from surface and decrease transmission of hotness (Fig. 4).

vi. Ocean Fertilization [23] = The addition of nutrients (in both micro and macro forms) to the sunlit upper layer of oceanic bulk mass for boosting growth phytoplankton through photosynthesis can confiscate carbon dioxide which culminates towards temperature reduction. Ocean fertilization is the most researched ocean geo-engineering technique, and it has the potential to mitigate both ocean acidification and global warming. It entails promoting the growth of phytoplankton, which use photosynthesis to turn CO_2 into oxygen. Around 50% of the world's photosynthesis is performed by microscopic phytoplankton.

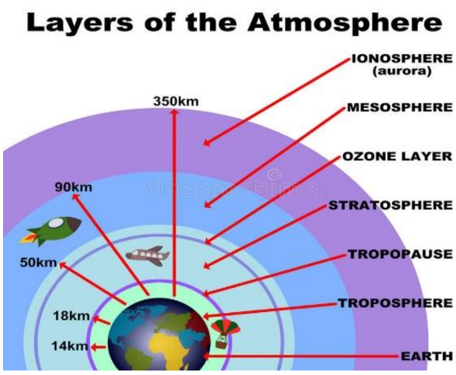

Fig. 3. Layers of the atmosphere
Source: https://www.dreamstime.com/

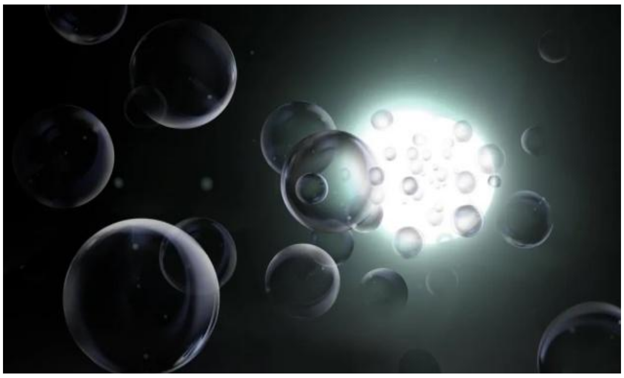

Fig. 4. "Space Bubbles" – The deflection of solar radiation using thin-film inflatable bubble rafts - massachusetts institute of technology
Source :https://scitechdaily.com/July 24,2022

- **Cryosphere**

i. Glacier Geoengineering [24] = Polar outlet glacier restriction (e.g. submarine embankments [15], building up barriers like submerged berm breakwater, restricting the basal freezing temperature to restrain the pressure melting point, contribute towards natural basal drying to slow ice streams as liquid water lubricating flow warm-based glaciers fast) to avert forfeiture ice mass.
ii. Restoration of Sea Ice [25] = The application of floating materials to the Ocean surface for improving reflective power to lower temperatures for retaining ice.

7. CONCLUSION

- Climate change (CC) has continued to wreak havoc on the planet's sustainability. The influence on the environment, economy, and society has continued to garner substantial attention from governments throughout the world. One of the major reasons that climate change is so contentious is because modelers overestimated their prediction ability.
- Contemporary moderation exertions and imminent promises appears as inadequate to match the temperature goals of Paris Agreement. As a result, research and debate on the potential use of wished-for macroclimate geo-engineering technologies, either through removal of atmospheric carbon dioxide or more far-reaching intercessions modifying the balance of radiative energy of earth, are intensifying. While investigations shows that numerous strategies might someday have the real ability of mitigating changes in climate, research is now in the premature stage with significant ambiguities and hazards.
- Climate geoengineering approaches, based on current knowledge, hardly can be relied upon to pointedly underwrite towards attaining the temperature goals decided in the Paris Agreement [26]. It is believed that enhanced detection of these processes is required in order to identify feasible mitigation activities while avoiding too optimistic assumptions and subsequent policy failures. The targets will be determined by future emission scenarios, which will be determined by national policies, as this is a global issue. Geo-engineering has been advocated as a viable method of reducing anthropogenic climate change, particularly rising global temperatures in the twenty-first century. While geo-engineering is an overall strategy to climate change, its feasibility and effectiveness are still debatable. Restraining inward solar energy or changing the cycle of carbon is broadly the two basic geo-engineering methods. According to new research from Harvard's John A. Paulson School of Engineering and Applied Sciences (SEAS), solar geo-engineering could be unexpectedly effective in mitigating some of the worst effects of global warming. While no one claims that solar geo-engineering can substitute pollution cuts and resolve climate change, it is stated that it can have a significant planetary chilling effect within a comparatively low cost. According to Harvard research (2018), it would roughly cost 2.25 billion $ per year over a period of 15-year [27,28]. In view of the foregoing, it is opined by the authors of this paper that the afforested measures under the banner of Geo-Engineering may be undertaken in the order of their technical feasibility and economic viability which may appear if implemented holistically.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Research JoOST

Slope Stability at the Juncture of Dredged Berth Pocket & Reclaimed Earth Embankment During Turbulence Caused by Rotation of Ship's Propeller

Sudipta Chakraborty[1,*], A.R. Kambekar[2], Arnab Sarma[3]

Abstract

For accepting vessels with large draft deepening of the berth pocket at any jetty is necessary by dredging. During berthing of ships, the bed soil particles in berth pocket gets eroded due to energy raised because of critical velocity, due to turbulence of the sea water in the pocket, caused by propeller's motion and also due to eddies formed during trimming of vessel. Such disturbances in bed soil particles and the energy in the water can endanger the berm slope due to splashing during run up and run down. For taking care of the stability of the slope connecting the dredged berth pocket and that of the reclaimed mass of embankment, the concerned safety factor plays an critical role at the juncture of the reclamation and the dredging. At the juncture of reclaimed soil mass and dredged pocket the criticality of submerged slope stability during hydraulic turbulence generated by propeller's movement during berthing of ship is discussed in this paper, with results from a large container terminal project at border of Arabian sea.

Keywords: Critical velocity, Reclamation, Dredging, Interface, Slope Stability

INTRODUCTION

The type of maritime infrastructure in ports which accommodate ships of various sizes and shapes vary depending on required draft of the vessel, availability of maneuvering area, bathymetry, coastline geometry, geotechnical features of the region, weather data and other pertinent factors.

A big chunk of land covering around 91 hectare was reclaimed from the sea during the creation of a container terminal on the western shore of Arabian Sea, and for berthing of large size container ships with higher draft, a long jetty was constructed at a far distance from the shore. For making any big terminal for catering to need of large container ships an area extended from the shore becomes necessary to avail the required draft for the design size vessel. At the same time the soil mass deposited in sea to construct the desired terminal needs proper consolidation and strengthening by driving vertical drains.

The soil particles below the seawater are basically sediments which are fragmented material, with varied specific gravity and mineral composition, primarily formed by disintegration of material from earth's crust. Depending on the particle size when sediments/soil particles are detached, they become susceptible to transportation by gravity, wind or water. The process of moving from original position is known as erosion. Initiation of movement of any submerged particle

***Author for Correspondence**
Sudipta Chakraborty
E-mail: diptasu@gmail.com

[1]Research Scholar, Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India
[2]Associate Professor, Department of Civil Engineering, SPCE, University of Mumbai, Maharashtra, India
[3]Head of Civil Engineering Department, The Assam Royal Global University, Guwahati, Assam, India

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happens when the velocity at the bed exceeds a critical velocity during sliding, lifting or rolling of a particular size of particle [1]. The force or motion required may vary as per self-weight of the particle and its shape and size. The coefficient of drag applicable to a bluff body may not hold good when the Reynolds Number is high [2]. For lifting of every particle there is a necessity of a Critical velocity [3].

In berth pockets close to the shore the ships behaviour is different from the usual degrees of motion because of eddy current at the aft portion and the Trimming and Squat phenomenon. Also, for large ships due to motion of propellor, the bow thruster, the water mass and the suspension of soil water slurry beneath ship’s keel generates a typical turbulent situation. In the said circumstances, at the juncture of dredging and reclamation zone the factor of safety becomes critical, while designing the slopes. The criticality of undersea slope stability due to hydraulic turbulence generated during ship’s maneuvering during berthing is explored in this paper, particularly at the interface of dredging and reclamation.

RECLAMATION

A huge area from the sea was required to be reclaimed for the establishment of a container terminal on the Arabian Sea coast to supplement the capacity of a container handling port on India's west coast. Construction in stages for edge stability, followed by ground improvement via band drain installation and surcharging for a calculated rest period, became simultaneously necessary for consolidation of the reclaimed mass. Land mode end-on technique was used for reclamation to ensure the stability of the reclaimed area’s edges. The experiences gained while carrying out the Dredging and Reclamation work for the said new container terminal development, especially the unique technical obstacles encountered at the interface of dredging and reclamation, are one-of-a-kind. The criticality and importance of Stability of dredged slope, including scour study at the interface of reclaimed material and dredge pocket, combating anf removing mudwaves became a point of concern for the designers.

STABILITY AT THE INTERFACE

A quay with approach trestle from the reclaimed area above the pile foundation was built independently at location illustrated in the schematic layout depicted in the Figure-1 below.

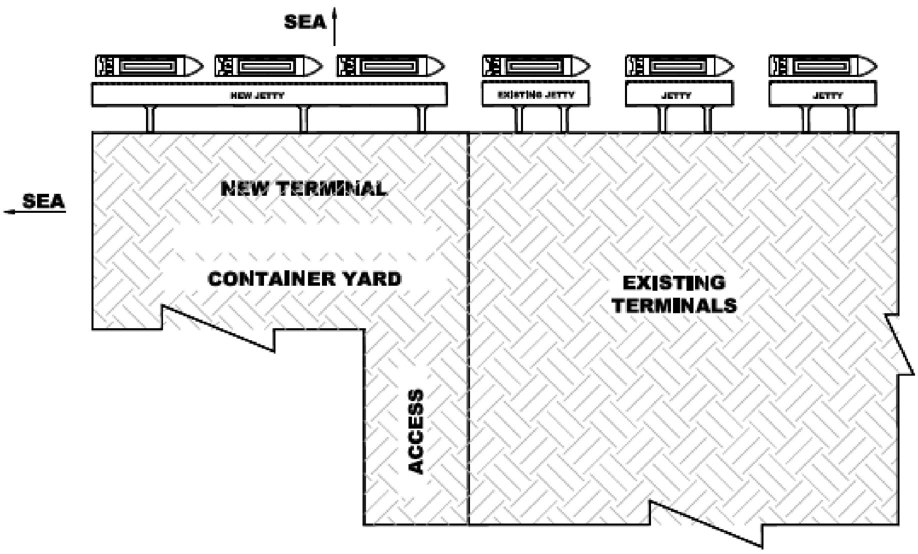

FIGURE-1 PLAN OF NEW TERMINAL

For deeper draught, the jetty had to be planned much away from the beach, and the space for the intended container terminal encompassing more than few square kilometres had to be reclaimed using locally available filler materials. Dredging was required at the berth pocket at the end of the reclaimed land mass, where finally an interface of ' Dredging' and 'Reclamation' occurred, as represented in Figure 2 below.

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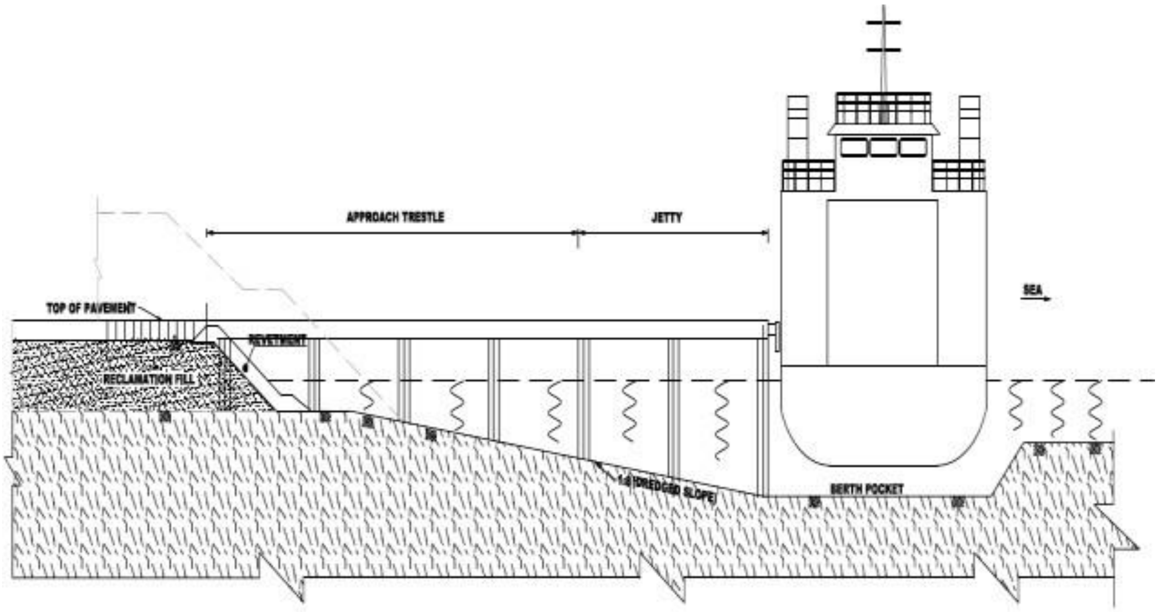

FIGURE-2 CROSS SECTION OF NEW TERMINAL AT THE INTERFACE

DESIGN PHILOSOPHY

A slope stability calculation for the dredged slope was performed both for stationary and dynamic earthquake forces following guidelines of PIANC and Gujarat State Disaster Management Authority (GSDMA) recommendations accepted by IIT Kanpur [6], utilizing the analytical method of half sine function interslice force function (Morgenstern and Price) [4] and SLOPE/W (GEO-SLOPE). Morgenstern and Price [4] believed that within the scope of limit equilibrium methods of stability analysis, no restriction on the geometry of the probable slip surface was required at the outset. In many circumstances, the critical surface deviates greatly from a circle or a plane, hence a method that allows for the analysis of surfaces of any shape is desirable [4], that discusses the assumptions required to render the problem as statically determinate.

To explore the stability of a soil mass with any slope and attributes, it was believed that the potential sliding body may be separated into a number of finite slices by vertical lines with coordinates

$x_0, x_1, x_2 \ldots\ldots\ldots x_n$.

This division is made in such a way that the fraction of the slip surface within each slice is linear, as are the interfaces between different soil types and pore pressure zones. If the calculated shear force at a slice interface required for equilibrium exceeded the shearing resistance that could be mobilized along the interface, the yield condition within the sliding soil mass would be breached. Because the total normal force acting on the interface has been determined, as well as the pore pressures and strength parameters obtained along the interface, the possible shearing resistance for the second assumption may be derived. A method for determining the factor of safety of a sliding body of any shape including materials with different shear strength values and pore pressures has been created[4].

It is entirely based on the concepts of limited equilibrium. If the predicted shear force at a slice interface required for equilibrium exceeded the shearing resistance that could be mobilized along the interface, the yield condition within the sliding soil mass would be broken [8].

All equilibrium and boundary conditions are needed to be taken into consideration when the governing equations are solved. The approach has been coded for a digital computer, and various applications are provided. There are additional comparisons with different ways of analysis. Because the soil is cohesive, the factor of safety was computed under seismic conditions using pseudo-static

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analysis, and the slope analysis was done using the total stress approach (based on undrained shear strength) for both temporary and permanent conditions. Because of the turbulence envisaged during the berthing of deep-drafted 18000 TEU capacity container ships [Figure 3] which will be caused by the movement of the bow-thruster and propeller, the dredging slope needs to be kept as smooth as possible when the fluid-soil interaction phenomenon was studied.

Figure 3. The Design Vessel
(Image Courtesy: Mærsk Mc-Kinney Møller)

For the purposes of such evaluations, the largest container ship, the Maersk Mc-Kinney Moller (Maersk Triple E-class), with a maximum speed of 23 knots, as opposed to the Emma Maersk's 25.5 knots, with following particulars has been examined.

Class and type	Triple E-class container ship
Tonnage	165,000 DWT
Length	399 m (1,309 ft 1 in)
Beam	59 m (193 ft 7 in)
Depth	14.5 m (47 ft 7 in)
Propulsion	Two shafts; fixed-pitch propellers
Speed	23 knots (43 km/h; 26 mph)
Capacity	18,270 TEU

The following vessel configuration was taken from PIANC recommendations [5] for analysis purposes.

Bow Thruster Location

i. The bow thruster is located in the middle of the ship
ii. The propeller tip and the ship's keel are at a distance of 0.5 m

Main Propeller Location

The main propellers on the largest ship are 24 m apart whereas in many other vessels it is at the centre of the beam width of the vessel.

The available soil's weak geotechnical parameter, was taken into account for slope stability analysis on an eroded slope. With a standard deviation of 6 kPa, the average cohesiveness of the soft clay is 9 kPa. The critical velocity for soil particles with a diameter of 2 m might range from 0.7 m/s to 1.5 m/s.

To assess the effect of scouring on the slope, it is important to remember that the slope's toe may

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recede over time, influencing the slope's top.

RESULTS AND DISCUSSION

The underwater inclined slope from reclaimed mass at the edge and that to the berth pocket slope was combed at 1:8 [(V): (H)], and the stability of this underwater slope was studied. The initial dredge slope's safety factor was calculated using the SLOPE/W programme. For obvious reasons the hydraulic conditions in the stated zone will be turbulent during the ship's berthing operation due to propeller's motion and bow thruster's movements, and as a consequence the surface of inclined slope will expose the slope to erosion. From the software it was found that for an average critical velocity of 1.15 m/s the dredging slope will erode at a low rate ranging from 0 to 0.1 m/year. Corresponding to the recurrent erosion over the expected lifetime as per the hydraulic analysis the degenerated degraded slope stands at 1: 6.5[(V): (H)] as stable which tantamount to the fact that once the 1:6.5 [(V):(H)] slope is created, no more erosion will occur. Under earthquake and stationary conditions, the eroded slope calculated with SLOPE/W software yields a factor of safety of 1.4 and 6.3, respectively. The eroded slope suits the intended purposes of stability (both long-term and short-term). The horizontal acceleration coefficient was chosen in accordance with the GSDMA specifications established by IIT Kanpur [6].

CONCLUSIONS

The following conclusions comes out from the preceding results and discussions [9].

i. The interface between the reclaimed embankment on the sea and its adjacent slope with the dredged berth pocket is required to be prudently prearranged to account for both temporary and permanent stability and scour. After a comprehensive investigation, the possibility for scour must be estimated.
ii. When the phenomenon of scour is caused by hydraulic turbulence, the steadiness of the side slope beaten by run up and run down water-beaten slope must be verified both under stationary conditions as well as vibratory loads due to earthquakes.
iii. If it is observed that the battered slope is insecure, appropriate scour protection must be installed, or the dredge slope must be compressed to the requisite extent.

The aforesaid steady slope of 1:6.5 [(V): (H)] at the bank of the berth pocket when no more erosion is expected to occur may however vary in future due to eddy currents hitting the inclined surface when generally sea level rise will happen as an impact of global warming. At the western coast of India, a sea level rise upto 600 mm has already been projected by 2050 excepting the effect of wind and wave [10]. The hydraulic turbulence situation during floating of ships and motions of propeller and bow thruster of vessels during ship's berthing in an increased water depth needs to be studied in further to verify the stability of side slope and the factor of safety for the given size of soil particles, particularly because of the fact that the keel clearance is expected to increase.

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Review JoOST

Complexities in the Structural Behaviour of Offshore Structural Members Subjected to Dynamic Loading

Chakraborty Sudipta[1,*], A. R. Kambekar[2]

Abstract

Offshore structural members in Maritime Structures are subjected to various kinds of loading starting from Dead Load of structures and Dynamic loads from wind, waves, currents and operational loads during berthing and mooring of ships and vessels. The stability analysis of the structural members also demands an insight into the elastic properties of the founding sea bed level. Due to requirement of transport of large volume of cargoes and related continuous enlargement of ship sizes the conventional approaches for designing demand revision particularly for frequent extreme weather events. A large number of tailormade softwares both for structural requirements (viz. STAADPRO etc.) modified for maritime requirements (viz. SACS etc.) the requirements are endless. This paper discusses some fundamental loading parameters on such structural elements to invite attention of scientists and maritime structural engineers for development of wholistic model of solution taking care of variation of everchanging factors.

Keywords: Dynamic Loading, Structural Behaviour, Offshore Structure, Elastic properties, Fundamental loading

INTRODUCTION

Dolphin structures for breasting and mooring of ships and Spuds for Offshore Jacket Platforms are exposed to various kinds of loads like static loads from superstructures and equipment, dynamic loading from wave and wind from the sea and berthing loads from ship's impact including aeroelastic and extreme weather loads. Study on the behaviour of dolphin structures, often made with a cluster of piles for rigid ones and more recently used large single pile flexible dolphins are important. Fenders are attached to Dolphins for absorbing the Berthing Energy from the Ships. Eventually during berthing operations, the fenders are subjected to horizontal reactions from the Berthing shock. The concept of flexible structure having end fixity in subsoil have proved to be better effective in absorbing the berthing energy by bending of the pile. While a pile is driven for foundation purpose, it is similar to a column subjected to vibrating axial loads having two kinds of soil-structure interaction responses. In some instances, the soil can be considered as behaving in an elastic manner although the nature of the soil beneath the pile at high energy level is almost always viscoelastic in nature, whereas in other case some of the energy released at the top of the pile is transmitted into the supporting soil adjacent to the pile. It is assumed that the soil remains in perfect contact with the pile. The soil-pile interaction behaviour varies with the nature of loading i.e, the frequency of excitation of vibration, the material property of both the soil and the pile and the pile geometry. This paper attempts to summarize the importance of fundamental loading parameters for such structures.

***Author for Correspondence**
Chakraborty Sudipta
E-mail: diptasu@gmail.com

[1]Former Chief of Civil Engineering Division of Haldia Port and PhD Scholar, Civil Engineering, The Assam Royal Global University, Guwahati, Assam, India
Guwahati, Assam, India; email: diptasu@gmail.com
[2]Associate Professor, Civil Engineering, Sardar Patel College of Engineering, Mumbai University, Maharashtra, India

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Literature Review

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Euler [1] initiated the development of the theory of stability of equilibrium configuration of elastic systems in 1744 when he solved the problem of a slender column loaded by axial compression forces. The first mathematical analysis of a problem in dynamic stability for a hinged column with a time dependent load was performed by Baliev [2] in 1924.The stability of lateral motion of a uniform bar subjected to pulsating periodic axial loads were also later studied by Mettler [3] in 1940 and others [4–6] (during 1943, 1952–1964) which are well documented in the book of Bolotin [7], (1961). Matlock and Reese [8] documented Generalized solutions for laterally loaded piles in 1961.Brown et al. [9] introduced use of Finite Element Method for this kind of studies in 1968. Ahuja et al. [10] in 1971, Burney et al. [11] in1975 investigated in the same field for various conditions and Thomas et al. [12] studied the effect of elastic foundation for Timoshenko Beam. Datta and Chakraborty [13] first studied the Parametric Instability of a Tapered Beam in 1982 using Finite Element Method. Shastry and Rao [14] had a similar study for a cantilever column with an intermediate concentrated periodic load in 1987. Similar studies were carried out by Datta and Nagraj [15] in 1988 on a bar with flaws supported on elastic foundation. Lal with Datta [16] investigated into the variation on a non-prismatic bar with localized damage subjected to an intermediate periodic axial load in 1991. A number of references (starting with Analysis of dynamic response of an embedded vertical pile using a visco elastic soil model- studied by Novak et al. '77-'78) are documented in the book of Bull [17], (1994). A generalized non dimensional analytical solution (for four special cases) has been discussed by Prof. West et al. [18] which can be utilized for calculation of buckling load of beams (supported in any combination of end bearing and uniform and/or depth-dependent skin friction) embedded in an elastic homogeneous or non-homogeneous Winkler foundation. Studies on "Stability of end bearing piles in a non-homogeneous elastic foundation and the same for friction piles in homogeneous as well as non-homogeneous elastic foundation" have been carried out by West, Heelis and Pavlovic [18, 19]. Chakraborty [21] developed a typical Stiffness Matrix for a Pile which can be used as an input for Stability Analysis of Related structural members by Finite Element Method. Vrouwenvelder et al. analyzed buckling loads using Physical Approximation Approach [22] and the concept has been applied to Raker Piles in rigid Dolphin structures [23].

Complexities

Piles are one of the most important structural elements widely used in offshore structures like terminals/jetties for oil/gas/other bulk cargo carriers in ports and harbours. Dynamic stability analysis of pile structure subjected to various loads in offshore structures are complex in nature during ship-shore interaction. While a pile is driven for foundation purpose, it can be considered as a type of column subjected to vibrating axial loads having two kinds of soil-structure interaction responses. In some instances, the soil can be considered as behaving in an elastic manner although the nature of the soil beneath the pile at high energy level is almost always viscoelastic in nature, whereas in other case some of the energy released at the top of the pile is transmitted into the supporting soil adjacent to the pile. It is assumed that the soil remains in perfect contact with the pile. The soil-pile interaction behaviour varies with the nature of loading i.e., the frequency of excitation of vibration, the material property of both the soil and the pile and the pile geometry.

$$[M]\{\ddot{q}\}+[K_e]\{q\}-[S]\{q\}=0$$

is the Matrix Equation for the free vibration of axially loaded column structure in which Rotary inertia and longitudinal inertia are neglected? In which {q} = generalized coordinates, [M] = mass Matrix, and [S]=stability Matrix which is a function of the axial load P. This is the generalized Mathieu-Hill equation for solution of Dynamic stability problems as found in reference literature [13]. By assuming a specific combination of loading and/or a determined impact from ship's berthing energy the actual governing equation can be developed for any specific dimension of a pile in a particular soil condition and a number of parameters can be found out. The fundamental natural frequency, the critical buckling load for the pile, and the zones of stability may be plotted in a parametric space by generalizing the solutions through non-dimensionalizing the concerned factors.

Berthing Energy

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The fender absorbs the berthing energy E in kNm and transfers the shock to the structure through its resilience [24, 25] which is given by (Figure 1, Figure 2):

$$E = 0.5*Cm*Mv*V_b^2*Ce*Cs*Cc,$$

where Cm is the hydrodynamic coefficient = 1+2T/B = 1.5 [BSI, 2014], where T, B, M_v, V_b, Ce are draft (m), beam (m), displacement (t), velocity normal to the berth (m/s) of the vessel and eccentricity coefficient respectively.

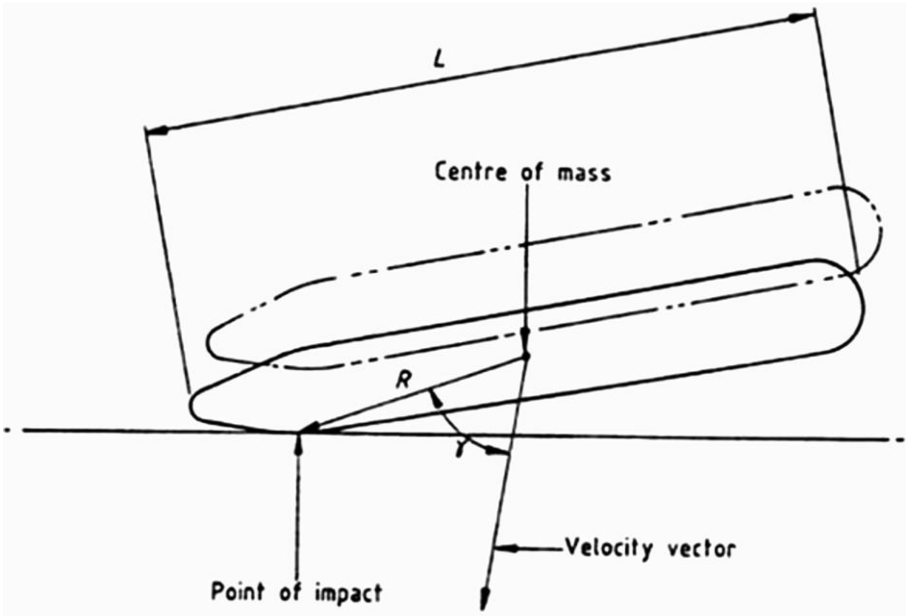

Figure 1. Schematic diagram Berthing of Vessel

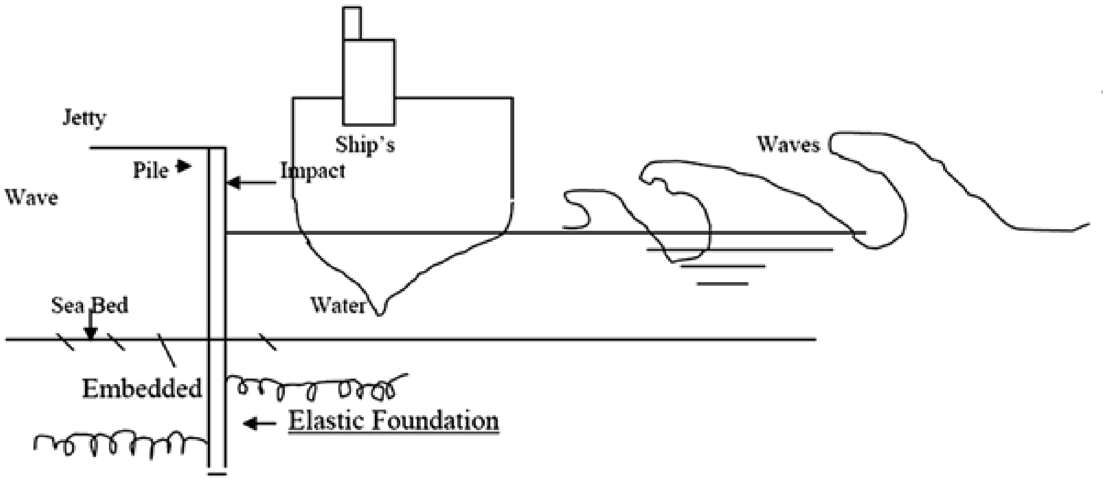

Figure 2. Schematic diagragm of loading

C_E is given by

$$C_E = \frac{K^2 + R^2 \cos^2\gamma}{K^2 + R^2}$$

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- K stands for ship's radius of gyration = (0.19Cb + 0.11) L; L stands for the length of the hull between perpendiculars (m).
- C_b is the block coefficient which is determined as = displacement [in (kg)/(L(m)] x beam [unit: (m)] x draft [unit: (m)] x density of water[unit (kg/m^3)];
- R stands for length upto the vessel's touching point from the mass centre (unit: m);
- γ stands for angle between the line joining the touching point of vessel to the mass centre and the direction of incidence of velocity.
- Cs is the softness coefficient which accommodates the proportion of the impact energy, absorbed by the hull of the ship. Research on absorption of energy by the hull of ship has not much been conducted and detailed reports are not available in plenty. However, in practice, conventionally value of C_S is considered between 0.9 and 1.0. C_S is taken as 0.9 for ships with continuous rubber fendering, For all other vessels C_S = 1.
- Cc is the berth configuration coefficient which accommodates that proportion of ship's energy which is engrossed by the padding effect of water stuck within the wharf and hull of the ship. A value of 1.0 for C_C should be used for open piled Wharf structures, and a value of Cc between 0.8 and 1.0 is recommended for use with a solid Wharf wall.

Appropriate assessment of the energy of ship's impact, to be absorbed needs to be calculated as per the standard code of practice based on kinetic energy developed for a ship with permissible berthing velocity [24]. The abnormal energy may be found by multiplying the normal energy by a factor of two as recommended by the British Code of Practice 6349 (Pt 4, section 2, 1965) [24]. While calculating the berthing energy the displaced mass of the ship, approach velocity of the ship and the virtual mass factor, the eccentricity factor, the softness factor for the fender, all needs to be taken care of suitably [20].

Research Approach

The appropriate governing equation for a given loading condition is to be formulated and the equation is to be solved to derive the stability and instability regions. The pile may be divided into a number of finite elements having nodal connections. For formulation of the Matrices the displacement patterns for the structural elements may be assumed as simple polynomials. To apply Finite Element Method, starting from first principle the matrices defining different parameters for discretized elements may be developed and later global assembly needs to be determined for solving the resulting matrix equations mainly in the form of eigen value problem to find out different boundaries of stability and instability for different situations. The problem now remains of generating the matrices for a specific case and the solution is to be found for the desired results.

CONCLUSION

Scientific developments are a continuous and never-ending process in all fields and is bound to undergo changes to cope with the modified requirements in civilization. The Offshore Structures of no exception. Ship sizes have been much wider and also deep drafted than before. Technological developments in dredging equipment have made it possible to go for deeper channels. Advancement in Artificial Intelligence, Super-fast computer processors, Remote Sensing Technology for obtaining more detailed information from Satellites and most recent challenges for ongoing sea level rises calls for much improved sustainable research and development in this sector and this paper highlights the need for a wholistic approach.

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AUTHOR BIOGRAPHY

Sudipta Chakraborty received his Bachelor of Engineering Degree in Civil Engineering, from Indian Institute of Engineering Science & Technology, Shibpore (Erstwhile known as Bengal Engineering College under University of Calcutta), India in the year 1978. He received his Master of Technology (Aeronautical Engineering) with specialization in Structural Engineering, from Indian Institute of Technology, Kharagpur, India in 1981. Being nominated by Government Of India as a Colombo Plan scholar, he obtained Dutch Government's sponsorship under Netherlands Fellowship Programme and he completed Master of Engineering (Hydraulic Engineering) in 1999 with specialization in 'Coastal Engineering and Port Development' from 'IHE Delft Institute for Water Education' (Formerly known asUnesco-IHE and earlier as ' IHE ' i.e., 'International Institute for Infrastructural Hydraulic and Environmental Engineering'), Delft, The Netherlands.

He retired as Head of Civil Engineering Division of 'Haldia Dock Complex' under 'Kolkata Port Trust', Ministry of Shipping, Government of India and thereafter worked in several big marine construction projects, including a few out of them funded by World Bank and also worked as consultant to various reputed engineering firms; his working experience totaling to 43 plus odd years. He has 9 Publications in International and 7 in National Journals and has authored a book on 'Sea Level Rise'.

He is a Fellow of Institution of Engineers (India) and Life Member of PIANC 'The World Association for Waterborne Transport Infrastructure' (Belgium) [Formerly known as Permanent International Association of Navigational Congress]. He has reviewed papers at Journal of Coastal Research, USA (2021) and Australasian Coasts & Ports Conference (in year 2017,2018,2019 & 2021). He is presently empaneled as an External Examiner at University of Mumbai for M. Tech level.

He joined as a PhD research scholar in 2019-20 Session at the Royal School of Engineering &Technology (Department of Civil Engineering), under The Assam Royal Global University at Guwahati, India. His research interests include Coastal Engineering as well as Sea Level Rise, Finite Element Method and Marine Structures.