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Tsunami Risk 3D Visualizations of Okha Coast, Gujarat (India)

V. M. Patel[1], M B. Dholakia[2], A.P. Singh[3]
[1]Lecturer, Civil Engineering Deparatment, K.D. Polytechnic, Patan – 384265, Gujarat, India
[2]Joint CEO, Gujarat Knowledge Society, Gandhinagar - 382 017, Gujarat, India
[3]Scientist, Institute of Seismological Research, Raisan, Gandhinagar- 382 009, Gujarat, India

Abstract*— The Makran coast is extremely vulnerable to tsunamis and earthquakes due to the presence of three very active tectonic plates namely, the Arabian, Eurasian and Indian plates. On 28 November 1945 at 21:56 UTC(03:26 IST), a massive Makran earthquake generated a destructive tsunami in the Indian Ocean. In India, the tsunami reached a height of about 11-11.5m in Gulf of Kachchh, Gujarat (Pendse, 1945; Pararas-Carayannis 2006). Modeling of inundation has been made for the Okha coast from the Makran source using Tsunami N2 numerical model. The bathymetry data is taken from ETOPO1 and land topography data was collected using SRTM data. The fault parameters of the earthquakes for the generation of tsunami are: fault area (200km length and 100km width), angle of strike, dip and slip (270°, 15° and 90°), focal-depth (10 km), and magnitude (8.0). Furthermore, the Okha coast of Gujarat is selected for 3D visualizations of tsunami risk for visualization, interpretation and accurate assessment of disaster risk. In this study, generation of 3D tsunami risk model in GIS/CAD environment is presented. The GIS/CAD based results are also validated with the available 1945 Makran tsunami simulated results (Jaiswal et al., 2009). Thus, these results will be useful in planning the protection measures against inundation due to tsunami and other Ocean disaster and in the implementation of a warning system.

Index Terms—**3D Visualization, GIS/CAD, Numerical Modeling, Tsunami Risk.**

I. INTRODUCTION

Tsunami is a phenomenon of gravity waves produced in consequence of movement of the Ocean floor that as a result of earthquakes, landslides, volcanic eruptions and large meteorite impacts. Gujarat state has the longest coastline in India about 1600 km, and has massive capital and infrastructure investments in its coastal regions. With rapid developmental activities along the coastline of Gujarat, there is a need for preparing tsunami risk 3D visualizations database using geoinformation technology. The coast of Gujarat is prone to many disasters in past. Some of the most devastating disasters that have struck the state in the last few decades include: the Morbi floods of 1978; the Kandla (port) cyclone of 1998; the killer earthquake in Kutch, January 26th 2001; and the flash floods in south Gujarat in 2005 and in Surat in 2006. Also in the past the coast of Gujarat was affected by tsunami (Jaiswal et al., 2009; Singh et al., 2012).

A. Historical Tsunami in the Arabian Sea

On 28 November 1945 at 1:56 am (local time), an 8.1 magnitude earthquake, off Pakistan's Makran Coast generated a destructive tsunami in the Northern Arabian Sea and the Indian Ocean (Berninghausen, 1966; Quit Meyer and Jacob, 1979; Ambraseys and Melville, 1982). the Western Coast of India has been affected by tsunamis in past (Figure 1). The Makran Subduction Zone (MSZ) is the possible source for creation of tsunami in The Western Coast of India and has been undergoing physical changes throughout the geological past.

The risk of tsunami on The Western Coast of India is high because of the phenomena associated with large earthquake on June 16, 1819. The best known of the historical tsunamis in the region is the one generated by the great earthquake of November 28, 1945 off Pakistan's Makran Coast (Balochistan) in the Northern Arabian Sea (Berninghausen, 1966; Quit Meyer and Jacob, 1979; Ambraseys and Melville, 1982). Its epicenter was at 24.5°N 63.0°E., in the northern Arabian Sea. The tsunami reached a height of 17 metre in some areas of the Makran coast and caused great damage to the entire coastal region of Pakistan. 12 to 15 m wave height was recorded in Ormara, near Gwadar. The earthquake was felt in Karachi too where ground motions lasted approximately 30 seconds, stopping the clock in the Karachi Municipality Building and interrupting the communication cable link between Karachi and Muscat (Oman). In Karachi the waves reached 3 metre high, first at 5:30 am, second at 7:00 am, third at 7:15 am and the fourth and the strongest at 8:15 am. The tsunami was responsible for loss of life and great destruction along the coasts of Iran, Oman and western India. More than 4,000 people were killed by both the earthquake and the tsunami but most deaths were caused by the tsunami. In India, the tsunami reached a height of about 11-11.5m in Gulf of Kachchh, Gujarat (Pendse, 1945; Pararas-Carayannis, 2006).

The tsunami wave reached up to height of 2m at Mumbai (Jaiswal et. al., 2008). At 8:15am, it was observed on Salsette Island i.e Mumbai (Newspaper archives, Mumbai). The tsunami reached as far south as Mumbai, Bombay Harbor, Versova (Andheri), Haji Ali (Mahalaxmi), Juhu (Ville Parle) and Danda (Khar). In Mumbai the height of the tsunami was 2 meters. Fifteen (15) persons were washed away. There was no report on damage at Bombay Harbor. Five people died at Versova (Andheri, Mumbai), and six more at Haji Ali (Mahalaxmi, Mumbai), several fishing boats were torn off their moorings at Danda and Juhu. The oldest known tsunami in the region may have been generated by a large magnitude earthquake, which occurred in the Indus delta/Kutch region in 326 B.C. Alexandra's fleet was washed away by the oldest tsunami of the Arabian Sea. Most of these events have not been adequately documented. On the western side of India, the earthquakes of 1524 and 1819 in the Kutch region probably generated destructive tsunamis. Destructive earthquakes and tsunamis have occurred in the North Arabian Sea throughout geologic history and in recent times. Historical tsunami event that affected the western coast of India shows in table 1 and figure 1.

Table 1: Historical Tsunami that Affected the Western Coast of India

NO	Year	Longitude (°E) /Location	Latitude (°N)	Moment Magnitude	Tsunami Source	Loss of Life
1	326BC	67.30	24.00		Earthquake	
2	1008	60.00[a]	25.00[a]	?	Earthquake	1000[*]
		52.3[b]	27.7[b]			
3	1524	Gulf of Cambay			Earthquake	
4	1819	Rann of Kutch			Landslide Volcanic	>2000[*]
5	1845	Rann of Kutch			Landslide Volcanic	
6	1897	62.30	25.00			
7	1945	63.00	24.50	8.1		4000[*]

[a] Rastogi and Jaiswal (2006)

[b] Ambraseys and Melville (1982)

[*] Both by earthquake and tsunami: Ambraseys and Melville, 1982; Bilham, 1999; Byrne et al., 1992; Dominey-Howes et al., 2006; Heck, 1947; Merewether, 1852; Murty and Rafiq, 1991; Murty and Bapat, 1999; Okal et al. 2006; Paras-Carayannis, 2006; Pendse, 1946; Rastogi and Jaiswal, 2006; Quittmeyer and Jacob,1979; Walton, 1864

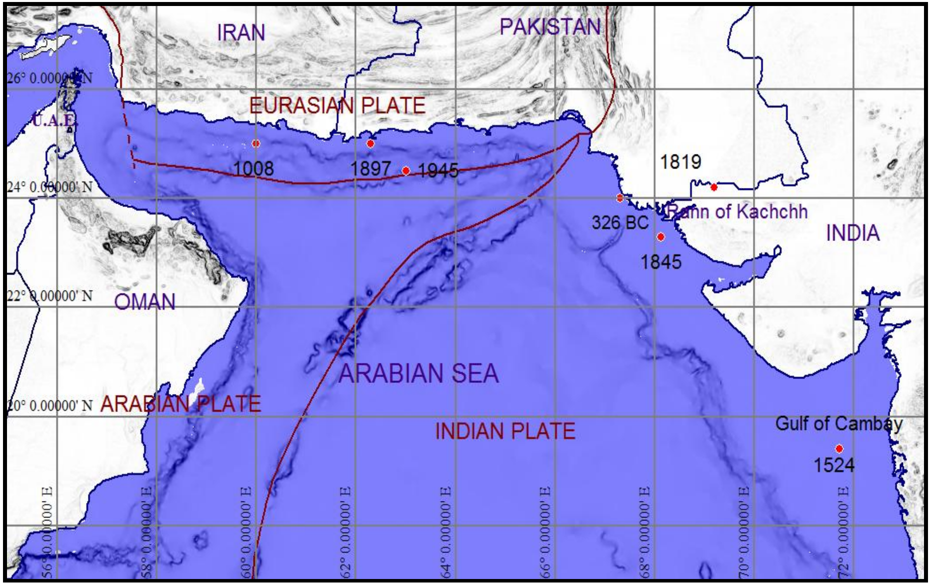

Fig 1. Historical tsunami that affected the western coast of India

B. Demand for Tsunami Risk 3D Visualizations

Visualization is the graphical presentation of information, with the goal of improving the viewer understands of the information contents. Comprehension of 3D visualized models is easier and effective than 2D models. 3D visualization models are important tools to simulate disaster from different angle that help users to comprehend the situation more detailed and help decision makers for appropriate rescue operations. 3D visualizations are tools for rescue operations during disasters, e.g., cyclone, tsunami, earthquake, flooding and fire, etc. 3D graphical representations significantly reduce the amount of cognitive effort and improve the efficiency of the decision-making process (Kolbe et al. 2005, Zlatanova 2008). 3D visualizations have the potential to be an even more effective communication tool (Kolbe et al. 2005, Zlatanova et al. 2002). 3D models particularly the city and building models are created by CAD software and scanned into computer from real world objects. The 3D visualization and animation can be performed in Computer Aided Design (CAD), and is powerful tool for conveying information to decision making process in natural disaster risk assessment and management.

II. METHODOLOGY

A. Data Used

In order to generate 3D visualization model of Okha Coast different sources of spatial data were used:
Topographical map in scale 1:50 000
Satellite images from the Google Earth
SRTM
GEBCO Bathymetrical data
Constructing 3D visual tsunami risk model of the Okha Coast divided into two stages, i.e. (1) numerical modeling of tsunamigenic historical earthquake and, (2) 3D modeling in GIS/CAD environment.

B. Numerical Modeling

The TUNAMI-N2 model was used for tsunami wave propagation, run up and inundation study along selected part of the Western Indian Ocean. The model TUNAMI-N2 was originally authored by Professor Fumihiko Imamura in Disaster Control Research Center in Tohoku University (Japan) through the Tsunami Inundation Modeling Exchange (TIME) program. TUNAMI-N2 is one of the key tools to study propagation and coastal amplification of tsunamis in relation to different initial conditions (Goto and Ogawa, 1992; Imamura and Goto, 1988; Imamura and Shuto, 1989; Goto et al., 1997, Shuto and Goto, 1988; Shuto et al., 1990).

The principal datasets required for the TUNAMI N2 numerical model are earthquake source parameters, topography and bathymetry data. The TUNAMI N2 model basically takes the seismic deformation as input to predict the run-up heights and inundation levels at coastal regions for a given tsunamigenic earthquake (Imamura et al., 2006). The seismic deformation for an earthquake has been computed using Smylie and Mansinha, (1971) formulation using the earthquake parameters like location, focal depth, strike, dip and rake angles, length, width and slip of the fault plane. TUNAMI-N2 uses second-order explicit leap-frog finite difference scheme. For the propagation of tsunami in the shallow water, the horizontal eddy turbulence terms are negligible as compared with the bottom friction. The equations are written in Cartesian coordinate (Imamura et al., 2006) as

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}=0 \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}=0 \tag{3}$$

Where M and N are the discharge in the x and y directions respectively, h the still water depth, η is the vertical displacement of water and D the total depth D=h+η. Bathymetry and elevation data are the principal datasets required for the model to capture the generation, propagation and inundation of the tsunami wave from the source to the land. The rupture parameters, as provided by Byrne et al. (1992), were used to model the source of 1945 earthquake and finite difference model. Static displacement on the surface of an elastic half space due to elastic dislocation was computed (Mansinha and Smylie 1971, Okda 1985). In this study, the most significant tsunamigenic earthquake in recent times was that of 28 November 1945 21:56 UTC (03:26 IST) with a magnitude of 8.0 (Mw), used for numerical modeling. Modeling of inundation has been made for the Okha coast from the Makran source using Tunami N2 numerical model. The bathymetry data is taken from ETOPO1 and land topography data was collected using SRTM data. Makran, Fault strike 270°: The fault parameters of the earthquakes for the generation of tsunami are: fault area (200km length and 100km width), angle of strike, dip and slip (270°, 15° and 90°), focal-depth (10 km), and magnitude (8.0).

C. 3D Modeling

In second stage 3D model of Okha coast is created in GIS/CAD environment, using satellite images. Satellite images integrated with Geographic Information System, can give information for assessment, analysis and monitoring of natural disaster such as tsunamis, storm surges, earthquakes and cyclones etc. The remote sensing techniques like photogrammetry, high resolution aerial oblique photography, Lidar and GPS speed up the 3D city model creation process (Verma et. al., 2006). The process of 3D Okha model generation further divided into two parts. The first part is related to processing of remotely sensed images. In these operation satellite images georeferenced by taking number of ground control points, and minimize root mean square error. The second part consists of vector layer operations. These operations include vector layer of tsunami risk map in GIS and 2D to 3D building layer operation in CAD environment. The vector layer of buildings and roads are measured in selected image region, having relatively large buildings. Very small buildings are difficult to recognize due to the resolution. The low-laying coastal territories along the Okha coast analyzed using the Shuttle Radar Topography Mission (SRTM) data. Potential risk sites for hazardous tsunami waves were identified and classified by analyzing areas showing heights below 3m, 5m and 7m above sea level.

III. RESULTS

The simulated Arabian Sea tsunami propagation generated due to above mention tsunamigenic earthquake indicated that the first tsunami wave reached on the in and around the Okha coast in Gujarat region (Jaiswal, et al., 2009; Singh et al., 2008). At Okha, positive tsunami waves arrive within approximately 2 hours and 30 minutes (figure 2). In this study the application of a numerical model to simulate tsunamigenic Makran event and an approach to estimate the extent of inundation along the Okha coast. It is found that if the tsunami strikes during the low tide, 1.5m tide, and 3.0m tide are inundated 100-300m, 100-500m and 100-600 m, respectively along the in and around the Okha coast (figure 3).

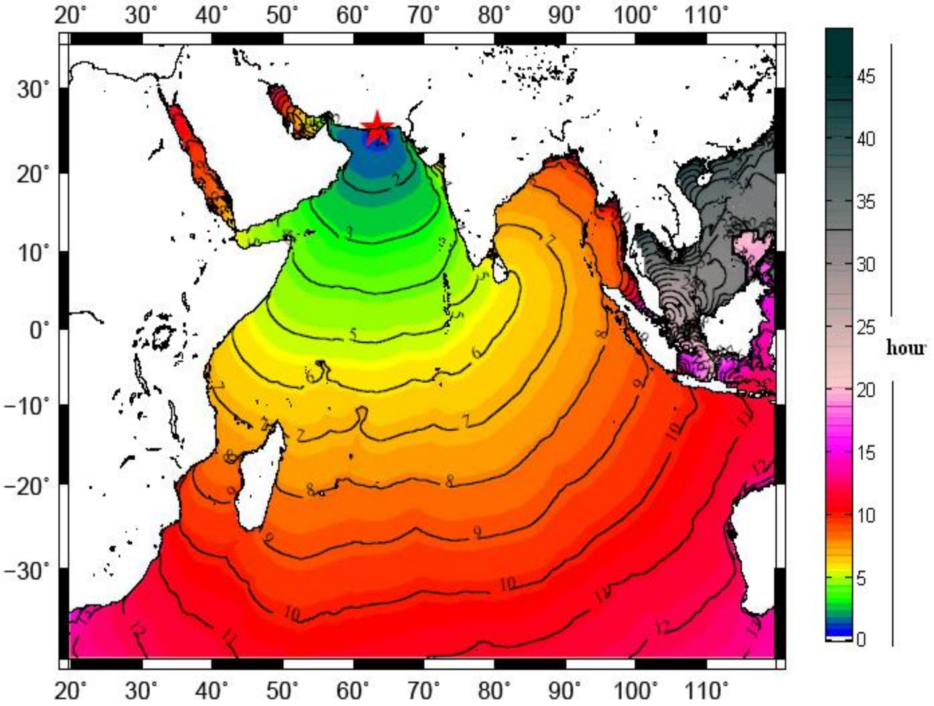

Fig 2. Hourly travel -time chart of tsunami wave that resulted from the Makran earthquake

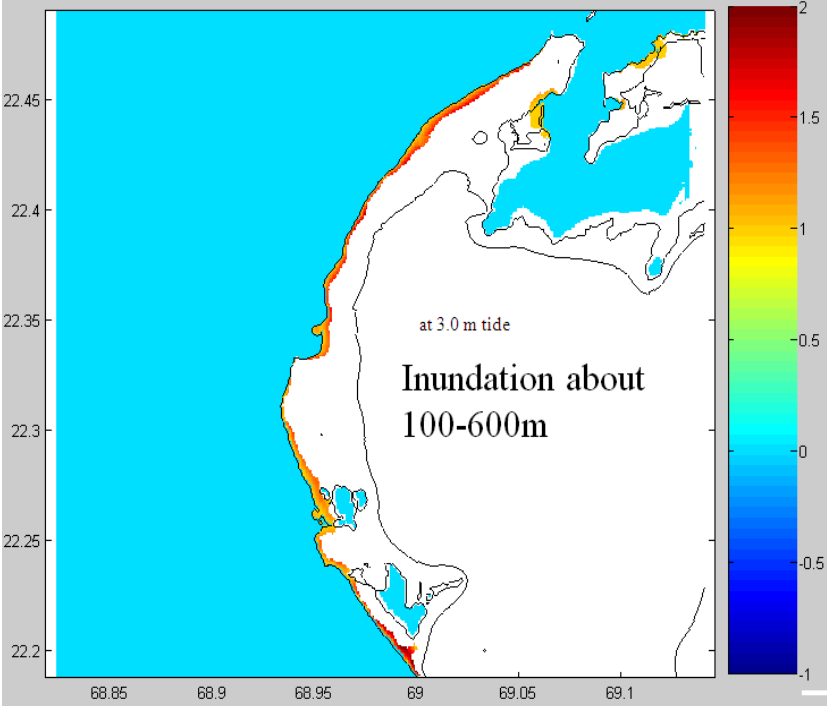

Fig 3: Tsunami inundation mapping during 3.0m tide along the Okha coast.

Based on the processed SRTM data, all low-laying coastal area potentially at risk of tsunami flooding have been identified and are shown in figure 4. This shows maximum extent of inundation with every 1m rise in sea level. In figure 5 coastal structure overlaid on digital elevation model and that shows coastal buildings potentially affected at different sea level rise scenarios.

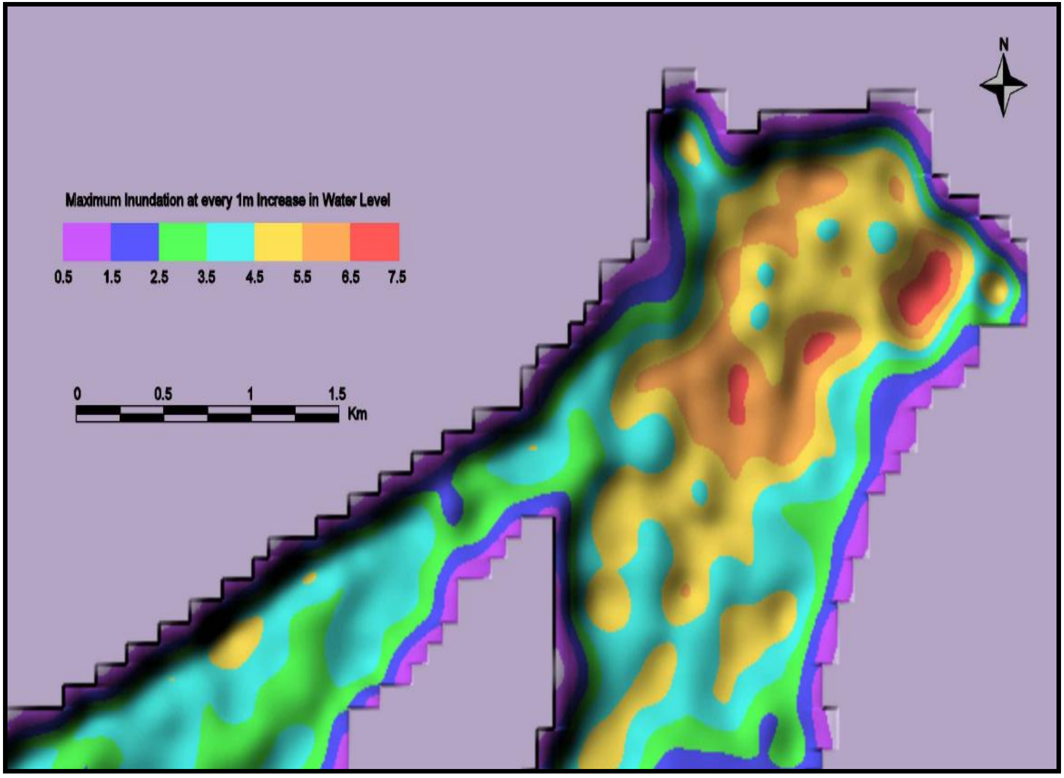

Fig 4: Coastal area of Okha potentially affected at different sea level rise scenarios

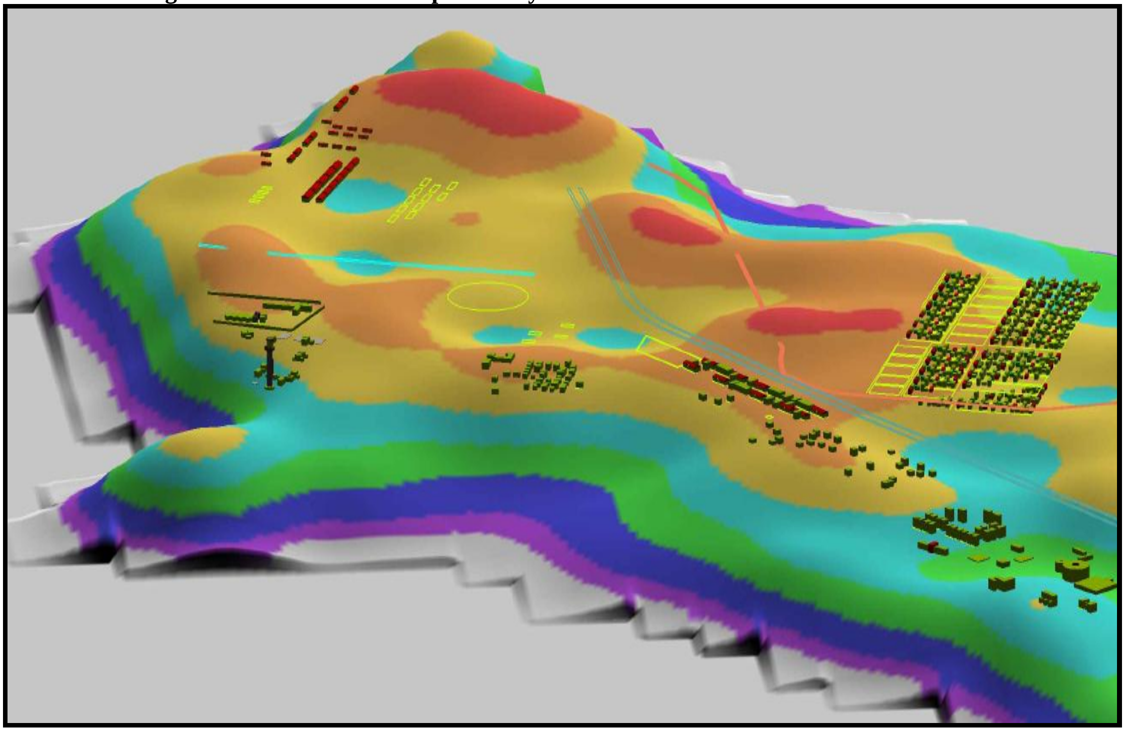

Fig 5: Structures potentially affected at different sea level rise scenarios

The creation and visualization of the 3D model is an endless operation. The generated 3D tsunami risk model of Okha can be seen in figure 6a, figure 6b and figure 6c from different viewing angles. A red, blue and green colors scheme was used by their respective susceptibility to tsunami risk as shown in figure 6. The classification of tsunami risk zone (susceptible zone) is based on elevation.

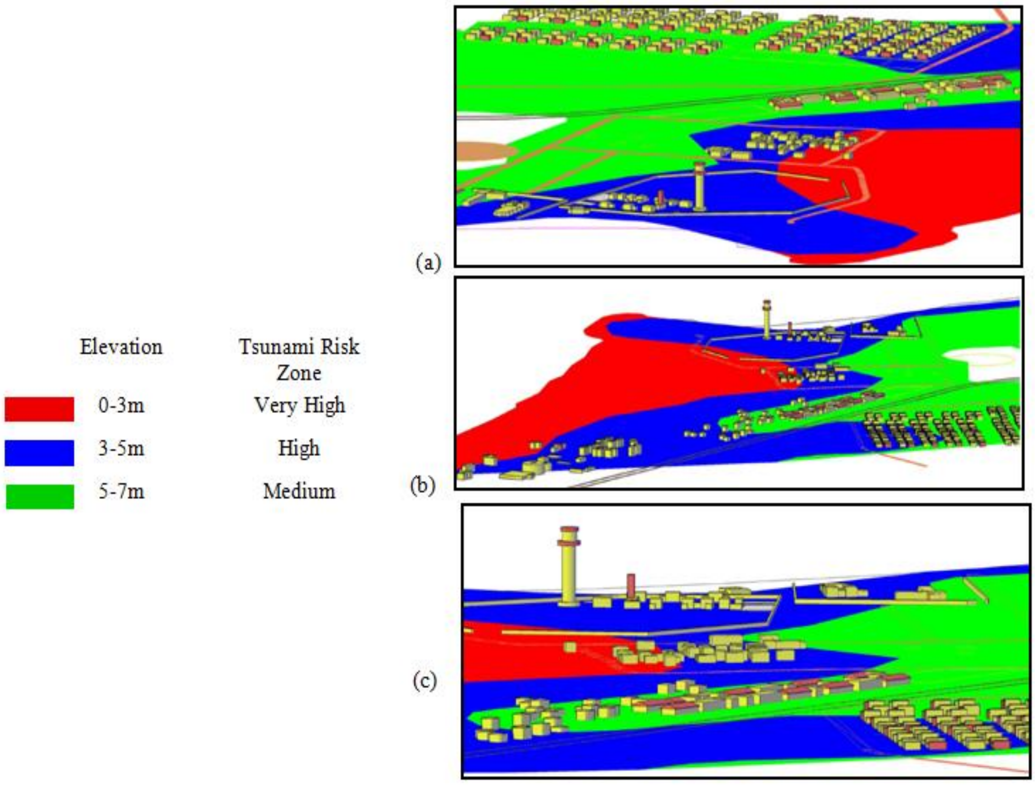

Fig 6: Visualization of 3D tsunami risk model of Okha with different viewing angles

IV. CONCLUSION

The Gujarat coast of India is vulnerable to tsunami attack. The Okha cost could be severely hit and economic losses would be too high. The lessons learnt from the Dec 2004 tsunami could be used for future planning. Ports, jetties, estuarine areas, river deltas and population in and around the Okha could be protected with proper methods of mitigation and disaster management. In future more need to focus on 3D visualization and animation of tsunami risk along the coast of Gujarat. The study performed to produces advantages of 3D GIS models and satellite images in tsunami risk assessment of the Okha coast, Gujarat. The main aim of 3D Okha model is to visualize each building's tsunami risk level which improves decision maker's understanding of disaster level. The merge of SRTM elevation data with satellite images is suitable for tsunami risk zone classification. Clubbing the advanced computer aided modeling, GIS based modeling, marine parameter measurements by ocean bottom seismometers and satellite, installations of tide gauges and tsunami detection systems and also using conventional and traditional knowledge, it is possible to develop a suitable tsunami disaster management plan.

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AUTHOR’S BIOGRAPHY

Vijendrakumar M. Patel received the B.E. and M.E. degrees in Civil Engineering from SVIT, Vasad, (2003-Distinction) and L.D. College of Engineering, Ahmedabad, Gujarat (2006-Distinction). Presently he is working as a Lecturer in Civil Engineering department of K.D. Polytechnic-Patan, Gujarat. He is currently pursuing his Ph.D. from K.S.V. University-Gandhinagar, Gujarat in the area of Geoinformation technology in tsunami risk 3D visualization. He has published around 15 research papers in various international and national journals/conferences. He has presented many research papers in international and national conferences/symposiums. He is life member of ISTE, India. He has seven years of academic experience at Ganpat University, PDPU and Government Polytechnic. He has supervising one M.E. Civil Engineering candidate for PG dissertation.

Shri Mrugen B. Dholakia received the Ph.D. degree in Civil Engineering from I.I.T., Bombay in 1998. Presently he is working as a Joint CEO of Gujarat Knowledge Society (GKS), Gandhinagar, Gujarat. He has twenty two year of academic experience at PG and UG level at Government Engineering colleges of Gujarat. He has supervised several Ph.D. and M.E. degree dissertations. . He authored/coauthored more than 40 research papers in peer-reviewed journals and conference proceedings.

Mr. A. P. Singh did M.Sc (Tech) Geophysics in 2002 from Banaras Hindu University (BHU), Varanasi, UP. He worked as JRF/Project Associate, at Indian Institute of Technology (IIT), Delhi, since August 2002 to August 2006. He is working as a Scientist at Institute of Seismological Research (ISR), Gandhinagar from August 2006. He did his PhD thesis on "Three Dimensional Seismic Structure and Seism tectonics of Kachchh Region, Gujarat, India: Implications for Seismic Hazard” at Department of Geophysics Kurukshetra University, Haryana. He is actively involved in research work namely Site Response, Loss estimation, Tsunami modeling, Seismic tomography and Climate change. He was awarded “Taiwan scholarships” by “Taipei Economic and Cultural Centre” New Delhi in 2004. He has attended workshop/training on seismology at ICTP, Italy and GFZ, Germany. He has supervised 5 candidates for M. Tech dissertation from various universities in India. He has published 20 research papers in international journals, 6 National Journals, 28 Papers Presented in Seminars/Symposia and 12 technical reports. He has served as scientific reviewer of international and national research Journals. He is also members of several scientific societies.