Vulnerability Assessment of Coastal Structure: A Study on Port Buildings

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Abstract
Ports are lifeline systems that function as storage and maintenance facilities for the transport of cargos. The port structures are frequently exposed to failure under severe seismic loading, for example, 1995 Kobe, 1989 Loma prieta, 1999 Kocaeli and 2001 Bhuj earthquakes. The scenario is more critical if the port sites are located within the seismically vulnerable area like Gujarat state of India. This clearly indicates the importance of port buildings and stability that can withstand natural disasters particularly earthquakes.
The main objective of this paper is to perform the nonlinear dynamic analysis of Kandla port building subjected to ground motion. Ground motions generated by Institute of Seismological Research (ISR), Gujarat at four locations on Katrol Hill Fault (KHF) and Kachchh Mainland Fault (KMF) were used in the analysis. Finally, the damage of the Kandla port building is estimated though fragility curves. The damage values obtained from fragility curve are 0.46, 0.17 and 0.88 for KHF Mandvi, NKF Jodiya and KMF Jhangi ground motions respectively.

Keywords
Port Building, Ground Motion, Damage, Fragility Curve, Applied Element Method

I. Introduction
Ports are lifeline systems that function as storage and maintenance facilities for the transport of cargos and people via water. The port structures are frequently exposed to failure under severe seismic loading, for example, the Hyogoken Nambu earthquake of January 17, 1995, has resulted in extended closure of the port of Kobe (Sixth largest container port in the world; Werner et.al., 1998) with extensive cost for repairs. The failure of particular port can be a major issue of national interest and huge economic loss.
The failure of port facilities during earthquakes is observed during the Loma Prieta earthquake of 1989, the Kobe earthquake of 1995, and the Kocaeli earthquake of 1999 (Werner et.al., 1998; PIANC 2001; Takahashi and Takemura 2005). The scenario is more critical if the port sites are located within the seismically vulnerable area like Gujarat state of India. During the Bhuj Earthquake of 2001, the liquefaction failures are reported in nearby port facilities (Madabushi and Haigh 2005; Dash et.al., 2008). Many pile supported buildings, warehouses and cargo berths in the Kandla port area were damaged during the same event. Dash et.al. (2008), showed that during Bhuj earthquake of 2001, 10 m thick loose to medium dense fine saturated sand was liquefied at Kandla port site and resulted severe damage at the mat-pile foundation which was supporting customs office tower. During strong shaking under seismic conditions, liquefaction, lateral spreading, slope instability, soil structure interaction, and site-specific ground motions are of the major geotechnical concerns for port structures. India has 12 major ports & 187 (Gujarat-40, Maharashtra-53, Goa-5, Daman & Diu-2, Karnataka-10, Kerala-13, Lakshadweep Islands-10, Tamil Nadu-15, Pondicherry-1, Andhra Pradesh-12, Orissa-2, West Bengal-1, Andaman & Nicobar Islands-23) non-major ports across 7,517 km long coastline. The geometry, material and soil details of Kandla port building (Jay Kumar and Deepankar, 2012) are described as follows:

II. Details of Port Building
Kandla port (latitude: 23.030N, longitude: 70.130E) is a protected natural harbor, situated in the Kandla Creek and is 90 kms from the mouth of the Gulf of Kachchh, India. Maharao Khengarji III of Kachchh built an RCC jetty in 1931 where ships with draft of 8.8 m could berth round the year. In 1955, Kandla was declared as a major port by the Transport Ministry of Independent India, and almost twelve states of India are dependent on the Kandla port for bulk cargo handling. Kandla port has 10 berths, 6 oil jetties, 1 maintenance jetty, 1 dry dock, and small jetties for small vessels with present cargo handling capacity around 40 million ton per annum (MTPA).
Mundra port (latitude: 22.740N; longitude: 69.710E) is located at 60 km west of Gandhidham in Kachchh district of Gujarat, India. The port was initiated in 1998 by the Adani Group as logistics base for their international trade operations when the port sector in India was opened for private operators. It is an independent and commercial port with 8 multipurpose berths, 4 container berths, and a single point mooring (SPM), presently capable of handling of 30 MTPA cargo and has future plan to achieve 50 MTPA by the fast track developments.
Hazira (Surat) port (latitude: 21.130N, longitude: 72.640E) is situated on the west side of the Hazira (District Surat) peninsula, Gujarat, India. The major development of the port in form of liquefied natural gas (LNG) terminal was carried out by Royal Dutch Shell group. Further developments in the form of construction of private bulk handling facilities by various manufacturing groups are in progress and considerable amount of money is invested to accommodate further vessel handling capacity for the future growth of this port.
Gujarat Port (latitude: 21.690N, longitude: 72.530E) is the most modern commercial port and storage terminal located at Dahej, (District: Bharuch), Gujarat, India in the Gulf of Khambhat (Cambay) on the west coast of India. The Port is capable of handling vessels of 6,000 DWT to 60,000 DWT, and the present Storage Terminal capacity is about 300,000 cubic meters of hazardous liquid and gaseous chemicals falling in ‘A’, ‘B’, and ‘General’ classes. The location also includes some private ports within the Dahej area including some future port facilities.
Among all the ports in Gujarat, Kandla port is one of the major ports which considered in this analysis. The main objective of this paper is to estimate the amount of damage to the port buildings subjected to various ground accelerations.

A. Building Details

1. Geometry

The building was founded on 32 short cast-in-place concrete piles and each pile was 18m long. The Port of Kandla is built on natural ground comprising recent unconsolidated deposits of inter bedded clays, silts and sands. The water table is about 1.230 m below the ground. Fig 1.shows the view of the natural grounds on which the Port of Kandla was built and elevation. The tower of the Port and Customs office considered for the present case study is located very close to Berths IV of the Kandla Port. The complete building details are given in Table 1.

2. Material

The material details are as follows:
Live load on floor = 2 kN/m^2;
Live load on roof = 0.75 kN/m^2;
Floor finishing = 1 kN/m^2;
Grade of concrete used = M_{25};
Poisson's ratio = 0.2

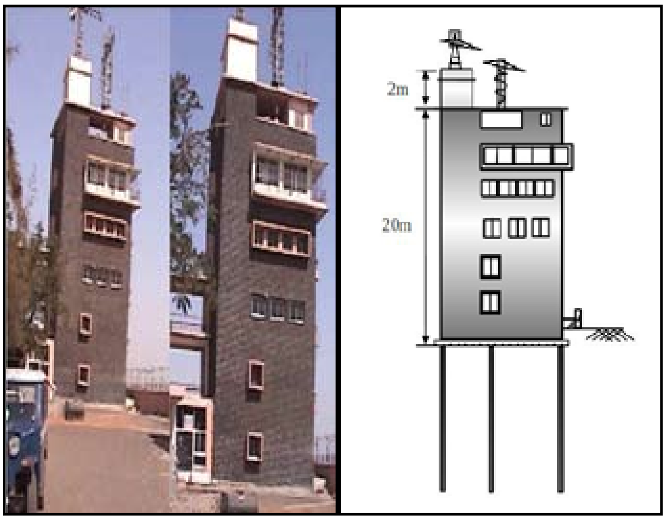

Fig. 1: (a) Elevation of Port Building and (b) Column Details of Port Building

Table 1: Port Building Details

Building Member	Dimension
Building height	22 m
Building plan at sill level	9.6 m x 9.8 m
Foundation raft	11.45 m x 11.90 m x 0.50 m
No. of columns	12
No. of piles	32
Length of pile	18 m
Diameter of concrete pile	0.4 m
Beam dimensions	0.25 m x 0.45 m
Slab thickness	0.15 m
Column-1 dimensions	0.45 m x 0.45 m
Column-2 dimensions	0.25x0.25 m

III. Numerical Modeling

The numerical techniques can be categorized in two ways. The first case assumes that the material as continuum like Finite Element Method (FEM). The other category assumes that the material as discrete model like rigid body spring model (RBSM), extended distinct element method (EDEM) and applied element method (AEM) (Hatem, 1998). The RBSM performs only in small deformation range. EDEM overcomes all the difficulties in FEM, but the accuracy is less than FEM in small deformation range. Till now there is no method among all the available numerical techniques, in which the behaviour of the structure from zero loading to total complete collapse can be calculated with high accuracy. The overview of FEM and AEM is as follows:

A. Finite Element Method

Finite element method is one of the most important techniques used in the analysis. In this method, elements are connected by nodes where the degrees of freedom are defined. The displacement, stresses and strains inside the element are related to the nodal displacements. The accuracy of the element depends on the size of element. The analysis can be done in elastic and nonlinear materials, small and large deformations except collapse behavior. At failure, the location of cracks should be defined before analysis which is not possible in collapse analysis. The problem becomes much more complicated when the crack occurs in 3D problems. In this analysis Takeda model is used. This model has been widely used in the nonlinear earthquake response analysis of RC structures.

B. Applied Element Method

Finite Element Method could not be able to simulate the complete collapse behavior of structure. Whereas, EDEM follow till structural collapse of the structure, but accuracy is lesser than FEM. The method which combines the advantages of both FEM and EDEM is AEM.

Applied element method is a discrete method in which the elements are connected by pair of normal and shear springs which are distributed around the element edges. These springs represents the stresses and deformations of the studied element. The elements motion is rigid body motion and the internal deformations are taken by springs only. The general stiffness matrix components corresponding to each degree of freedom are determined by assuming unit displacement and the forces are at the centroid of each element. The element stiffness matrix size is 6x6. The modelling of structure in AEM is shown in fig 2. However the global stiffness matrix is generated by summing up all the local stiffness matrices for each element.

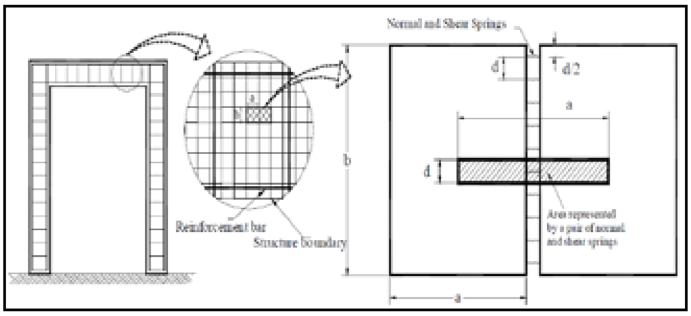

Fig. 2: Modeling of Structure in AEM

The material model used in this analysis is Maekawa compression model (Tagel-Din Hatem, 1998). In this model, the tangent modulus is calculated according to the strain at the spring location. After peak stresses, spring stiffness is assumed as a minimum value to avoid having a singular matrix. The difference between spring stress and stress corresponding to strain at the spring location are redistributed in each increment in reverse direction. For concrete springs are subjected to tension, spring stiffness is assumed as the initial stiffness till it reaches crack point. After cracking, stiffness of the springs subjected to tension is assumed to be zero. For reinforcement, bi-linear stress strain relationship is assumed. After yield of reinforcement, steel spring stiffness is assumed as 0.01 of initial stiffness. After reaching 10% of strain, it is assumed that the reinforcement bar is cut. The force carried by the reinforcement bar is redistributed force to the corresponding elements in reverse direction. For cracking criteria (Hatem, 1998), principal stress based on failure criteria is adopted. The models for concrete, both in compression and tension and the reinforcement bi-linear model are shown in fig 3. To determine the principal stresses at each spring location, the following technique is used in this analysis. The shear and normal stress components at point A are determined from the normal and shear springs attached at the contact point location shown in fig 4. The secondary stress σ_2 from normal stresses and at point B and C can be calculated by using the equation given below:

$$\sigma_2 = \frac{x}{a}\sigma_B + \frac{a-x}{a}\sigma_c \qquad (1)$$

The principal tension is calculated as:

$$\sigma_P = \frac{\sigma_1 + \sigma_2}{2} + \sqrt{\left(\frac{\sigma_1 - \sigma_2}{2}\right)^2 + \tau^2} \qquad (2)$$

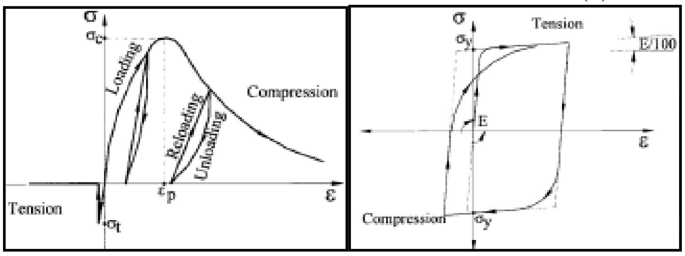

Fig. 3: Material models for concrete and steel

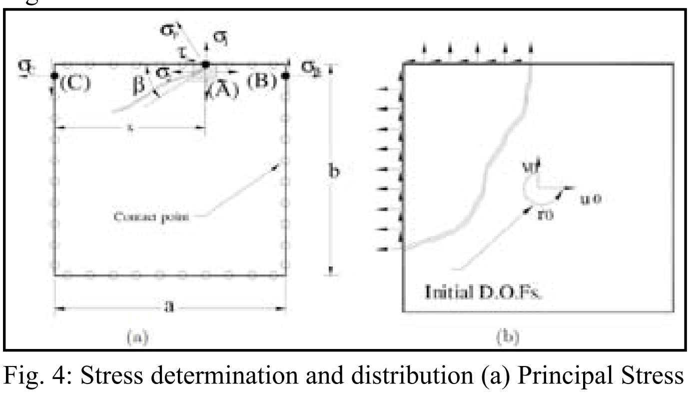

Fig. 4: Stress determination and distribution (a) Principal Stress determination and (b) Redistribution of spring forces at element edges

The value of principal stress (σ_p) is compared with the tension resistance of the studied material. When σ_p exceeds the critical value of tension resistance, the normal and shear spring forces are redistributed in the next increment by applying the normal and shear spring forces in the reverse direction. These redistributed forces are transferred to the element center as a force and moment, and then these redistributed forces are applied to the structure in the next increment.

IV. Non-Linear Time History Analysis

A study has been conducted to study the dynamic nonlinear behavior of port building. The dynamic properties of the building are as follows: The fundamental period of structure is 0.77 sec and the period of structure from mode-2 to mode-7 are 0.225 s, 0.112 s, 0.072 s, 0.057 s, 0.049 s and 0.038 s respectively. The procedure for finding out the response of the structure is already discussed in the earlier sections. Now the structure is subjected to several ground motions from different places of Bhuj namely, Kachchh Mainland Fault: Bharuch, Dholera, Lalpur and Mandvi; Katrol Hill Fault: Bharuch, Dholera, Lalpur and Mandvi. The geographical locations of Dholera, Bharuch Lalpur and Mandvi are (22.25, 72.2), (21.74, 73.01), (22.35, 69.96) and (22.82, 69.35). The characteristics of ground motions are as follows:

A. Ground Motion Characteristics

For engineering purposes, (1) amplitude (2) frequency and (3) duration of the motion are the important characteristics (Steven L Kramer, 1996). Horizontal accelerations have commonly been used to describe the ground motions. The peak horizontal acceleration for a given component of motion is simply the largest (absolute) value of horizontal acceleration obtained from the accelerogram of that component. The largest dynamic forces induced in a certain types of structures (very stiff) are closely related to the PHA.

Earthquakes produce complicated loading with components of motion that span a broad range of frequencies. The frequency content describes how the amplitude of ground motion is distributed among different frequencies. The frequency content of an earthquake motion will strongly influence the motion of structure. The broad band width of the Fourier amplitude spectrum is the range of frequencies over which some level of Fourier amplitude is exceeded. Generally band width is measured at a level of 0.707 times of maximum Fourier amplitude. In our analysis Bracketed duration is used for calculating the duration of ground motion. The ground motion records and its Fourier amplitude spectrums are shown in fig. 5.

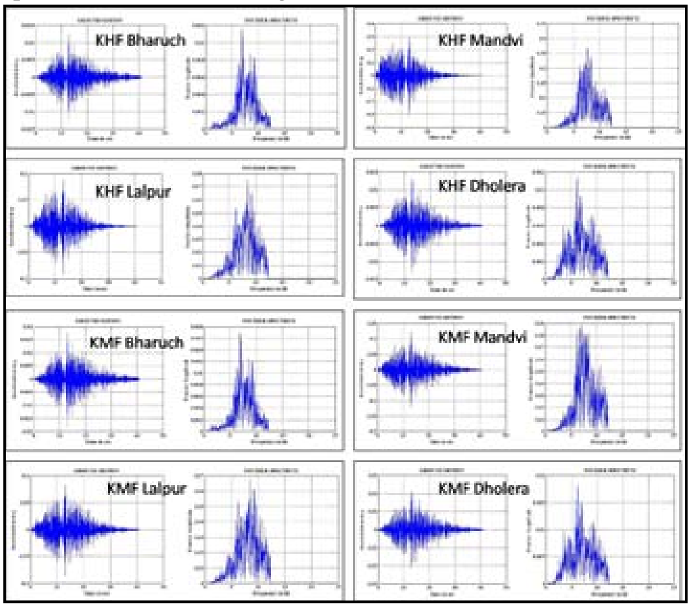

Fig. 5: Ground Motions and Fourier Amplitude Spectra

B. Response of Structure

In order to begin any physical system, it is necessary to formulate it in a mathematical form. The general dynamic equation for a structure is given below.

$$M\ddot{U} + C\dot{U} + KU = \Delta f(t) - M\ddot{U}_g \qquad (3)$$

Where [M] is mass matrix; [C] is damping matrix; [K] is nonlinear stiffness matrix; Δf(t) is incremental applied load vector ΔU and its derivatives are the incremental displacement, velocity and acceleration vectors respectively. The above equation is solved numerically using Newmark's β method (Anil k Chopra, 2001). For mass matrix the elemental mass and mass moment of inertia are assumed lumped at the element centroid so that it will act as continuous system. The elemental mass matrix in case of square shaped elements is given below.

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} D^2 t\rho \\ D^2 t\rho \\ D^4 t\rho / 6.0 \end{bmatrix} \quad (4)$$

Where D is the element size; t is element thickness and ρ is the density of material. From the above equation it is noticed that [M1] and [M2] are the element masses and [M3] is the mass moment of inertia about centroid of the element. The mass matrix is a diagonal matrix. The response of the structure is very near to the continuous/distributed mass system if the element size becomes small. If the damping is present, the response of the structure will get reduced. The damping matrix is calculated from the first mode as follows:

$$C = 2\xi m \omega_n \quad (5)$$

Where ξ is damping ratio and ωn is the first natural frequency of the structure. For finding out the dynamic properties such as natural frequencies of a structure requires eigen values. The general equation for free vibration without damping is:

$$M\ddot{U} + KU = 0 \quad (6)$$

For a non trival solution, the determinant of the above matrix must be equal to zero. The solution of determinant of matrix gives the natural frequencies of the structure.

The displacement response of the structure is calculated using Newmark's β method. Initially the response is calculated with an element size of 0.25 m. As the size of the element decreases, the response level will get saturate. This means the response will be same with decreasing the element size further. The structure is modelled in AEM and the elevation views are shown in fig. 6.

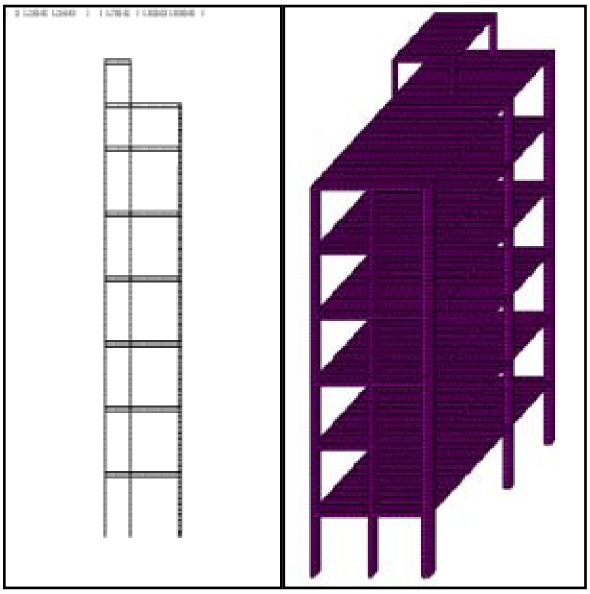

Fig. 6: 2D and 3D Elevation of Port Building Modelled in AEM

To find out the behavior of the port building, 8 different ground motions at Dholera, Bharuch, Lalpur and Mandvi on the faults Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF) generated by Institute of Seismological Research (ISR) are applied to the structure. For all the ground motions, the response is calculated at the top of port building. The fundamental period of the structure in first mode is 0.77 sec. The second and third modes are 0.225 and 0.11 sec respectively. The predominant frequencies range of ground motions is 0.11-0.18 sec which is far from the fundamental period of the ground motion. The third mode frequency of the structure is getting matched with predominant period of all the ground motions. It means that the structure is predominantly vibrated in third mode. The responses of the structure for all the ground motions are plotted in figure 7.

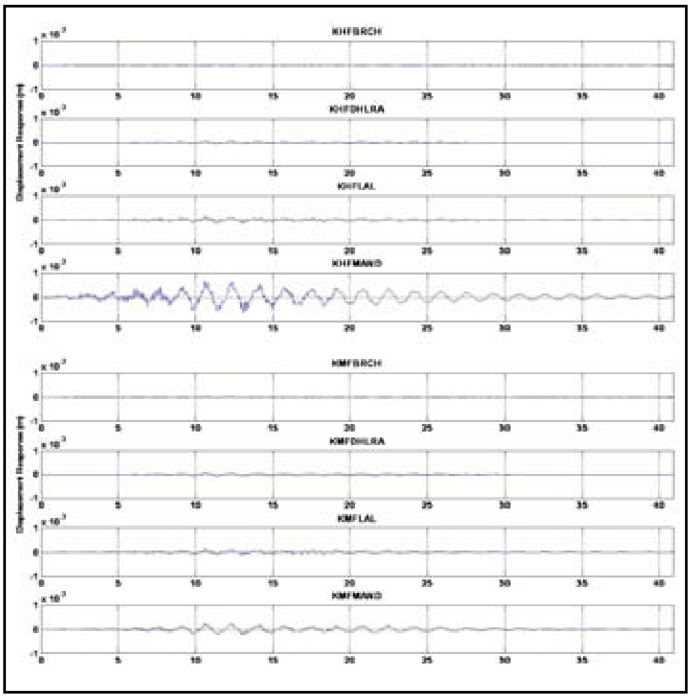

Fig. 7: Displacement responses of port building due to 8 ground motions

Since the structure is modeled in 3D and with vertical irregularity, it has response in all three directions. The calculated responses are in flexible direction of the building. The displacement responses of the structure are 2.2E-5, 5.3E-5, 1.5E-4, 6.5E-4, 3.2E-5, 8.3E-5, 1.2E-4 and 2.4E-4 m. From the analysis, the maximum response obtained from KHF Mandvi ground motion is 6.5E-4 m. This is because of high PGA value among all the ground motions. But, the response of the structure will effect because of frequency not from PGA. It would experience more response if the fundamental period falls in the range of predominant period of ground motion. But, in this case, the fundamental period of the structure is far from the predominant period of the ground motion. The frequency range of ground motions is 5-10 Hz and the fundamental frequency of the structure is 1.3 Hz which is far from the frequency range of ground motions. From the analysis, it is observed that the nonlinear response of the structure is similar to linear. It means that the structure has not yielded for the ground motions given.

V. Pushover Analysis

About 130 RC buildings collapsed during 2001 Bhuj earthquake in Ahmadabad alone. Nearly 25000 other buildings are designed and constructed in the same manner in these areas. Though these structures are still standing, serious concerns have been arisen on their safety during future earthquakes. There are many cities with these types of structures, their safety cannot be guaranteed, they may be seismically deficient. There is an urgent need to assess the seismic vulnerability of buildings in urban areas of India as an essential component of a comprehensive earthquake disaster risk management policy. Detailed seismic vulnerability evaluation is a technically complex and expensive procedure and can only be performed on a limited number of buildings. It is therefore very important to use simpler procedures that can help to rapidly evaluate the vulnerability profile of different types of buildings, so that the more complex evaluation procedures can be limited to the most critical buildings.

Pushover analysis is mainly to evaluate existing buildings and retrofit them. It can also be applied for new structures. RC framed buildings would become massive if they were to be designed to behave elastically during earthquakes without damage also they become uneconomical. Therefore the structures must undergo damage to dissipate seismic energy. To design such a structure, it is necessary to know its performance and collapse pattern. To know performance and collapse pattern non linear static procedures are helpful. It is an incremental static analysis used to determine the force-displacement relationship, or the capacity curve, for a structure. The analysis involves applying horizontal loads, in a prescribed pattern, onto the structure incrementally; pushing the structure and plotting the total applied lateral force and associated lateral displacement at each increment, until the structure achieve collapse condition. A plot of the total base shear versus roof displacement in a structure is obtained by this analysis that would indicate any premature failure or weakness. A procedure for assessing vulnerability is given in fig. 8

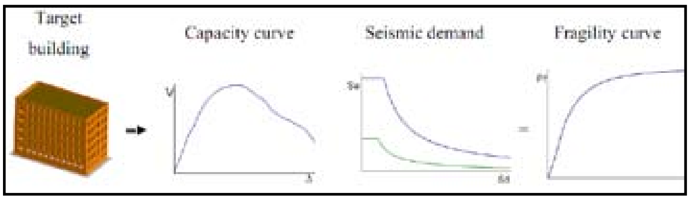

Fig. 8: Vulnerability Assessment of Structure (Amin Karbassi, 2010)

Now to get the load vs displacement curve for a structure, the structure is pushed using either load control or displacement control. In this analysis displacement control is used till complete collapse of the structure. The load vs displacement plot is shown in fig. 9. In this analysis, no need to specify plastic hinges. All these effects are incorporated in the analysis. The failure locations, cracking in concrete and yield of steel are determined automatically. The stiffness of the structure getting reduced when the first crack starts or the first spring fails. The spring fails when the principle stress exceeds the limited value. Now the first spring fails at (4.75 m, 18.48 m) which causes crack in the structure. In this analysis, steel failure is also allowed. When the structure reaches the peak load value in the load vs displacement curve, it starts coming down for further increase in the displacement.

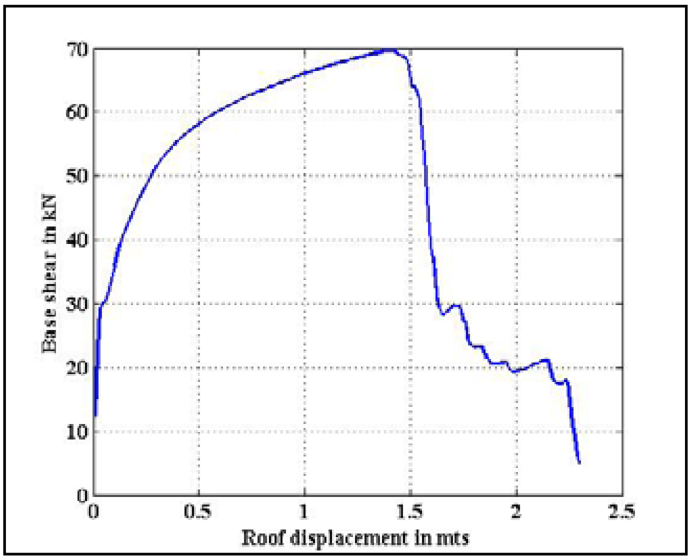

Fig. 9: Base Shear vs Roof displacement for the port building

VI. Fragility Analysis For Port Building

Now the area under the load vs displacement curve is the total energy dissipated in the structure. We calculated elastic and inelastic energy of the structure at each and every displacement. The damage parameter is denoted as the ratio of inelastic energy to the total energy of the structure. The displacement values can be converted to spectral displacement and then converted to spectral acceleration values using 4π(SD)/T2. Where SD=spectral displacement and T=time period. Fig. 10 gives the damage curve for different PGA values of ground motion. From figure 33 we can estimate the amount of damage to the port building for the given ground motion PGA value.

For the Kandla port building, the damage value is 0.2 when KHF Mandvi ground motion is applied to it. For other port buildings like Mundra, Hajira and Dhej port buildings, the PGA value will be calculated and based on it we can estimate the damage.

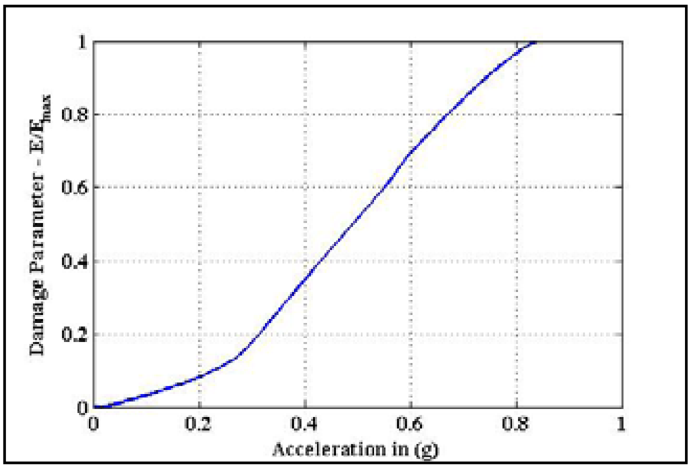

Fig. 10: Damage Curve for the Port Building for Different PGA Values

The acceleration response spectrum is drawn at KHF Mandvi, NKF Jodiya and KMF Jhangi. The PGA values at these stations are 0.218g, 0.377 g and 0.396g respectively. Spectral acceleration can be found out for the period of structure. From the analysis, the fundamental natural period of the structure is 0.77 sec, 0.225 sec and 0.11 sec in 1st, 2nd and 3rd modes respectively. Table 2 shows the comparison of damage for different spectral accelerations obtained from acceleration response spectra of KHF Mandvi, NKF Jodiya and KMF Jhangi. From the fragility curve, structure is not get damaged for the ground motions mentioned in above section, except KHF Mandvi ground motion. It gets damage for the spectral accelerations from fig. 11.

Table 2: Comparison of Damage for Spectral Accelerations Obtained From Acceleration Response Spectra of KHF Mandvi, NKF Jodiya and KMF Jhangi

S.No	Ground Motion	Spectral Acceleration (g)	Damage
1.	KHF Mandvi	0.47	0.46
2.	NKF Jodiya	0.23	0.17
3.	KMF Jhangi	0.76	0.88

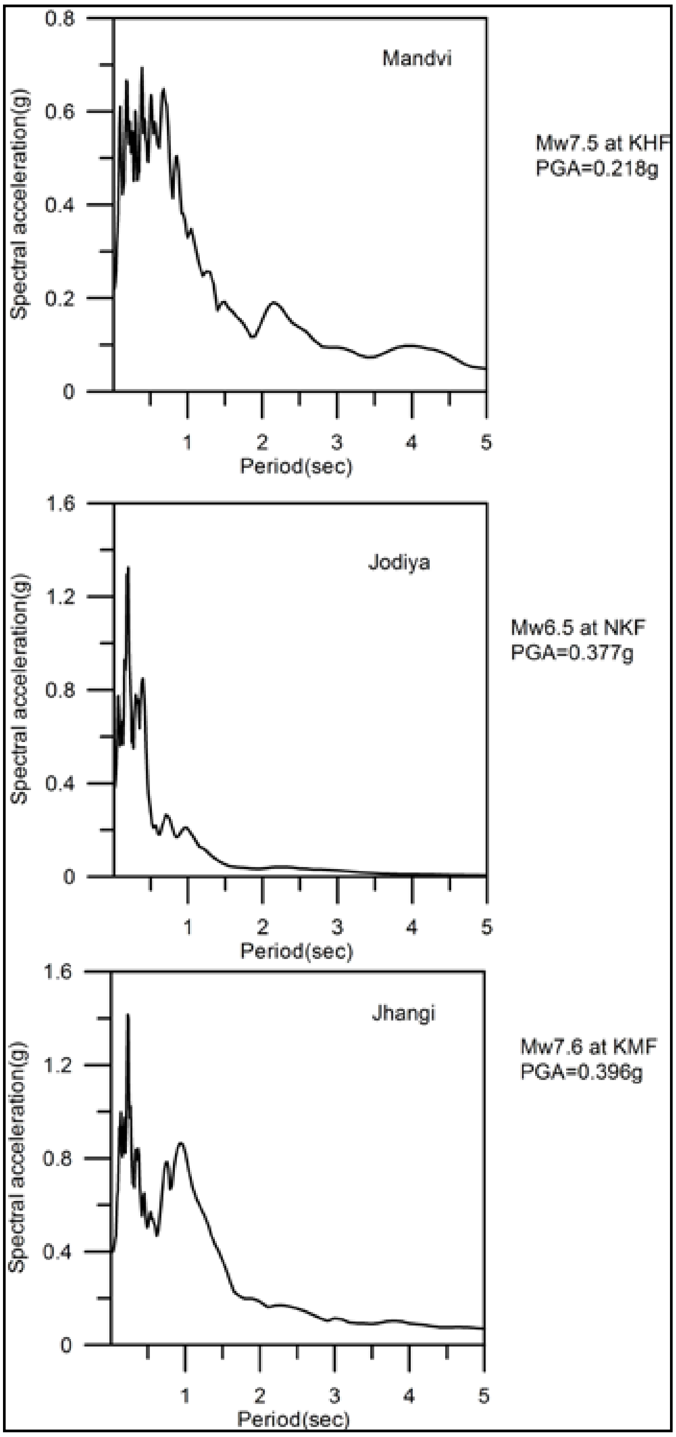

Fig.11: Spectral Accelerations Plotted at Mandvi, Jodiya and Jhangi

VII. Conclusion

From the analysis, it can conclude that the responses of the structure for different ground motions are very less even in nonlinear analysis. Because the fundamental frequency of the structure is far away from the predominant frequency range of ground motions. If the structure is fallen in predominant range, the response of the structure would be more.

The damage of the structure is easily identified from fragility curves for different ground motions. Based on the ground motions data, the maximum PGA is 0.308 g for KHF Mandvi ground motion. But the response of the structure is very less for this ground motion also because of non predominant frequency range. If the structure's fundamental frequency is predominant with the ground motion frequency, the damage will be around 0.2. The damage will be less than 0.4 for all other ground motions because of less PGA values. From acceleration response spectra of KMF Jhangi, more damage is observed.Based on the fragility analysis of port building the following recommendations are drawn.

1. For the Kandla port building, the damage value is 0.2 when KHF Mandvi ground motion is applied to it. and
2. The PGA values at KHF Mandvi, NKF Jodiya and KMF Jhangi stations are 0.218g, 0.377 g and 0.396g respectively. The damage of the port building is calculated 0.46, 0.17 and 0.88 for KHF Mandvi, NKF Jodiya and KMF Jhangi.

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Pradeep K Ramancharla holds his PhD degree from University of Tokyo, Japan. Presently, he is professor of Civil Engineering and head of Earthquake Engineering Research Centre (EERC) at IIIT Hyderabad. His research interests are numerical modelling of faults and tectonic plates, collapse simulation of buildings, seismic evaluation and strengthening of buildings and concrete codes in India. Presently he is a panel member of CED 2: IS 456 and IS 1343.