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Structural Design of Skyscrapers Susceptible to Seismic Activity and Soil Liquefaction

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Abstract: The design of skyscrapers involves lot of aspects such as the building must withstand heavy dead loads, should have safety measures against fire, floors must be easily accessible, and should have resistant against wind and seismic loads that can be detrimental to the safety of the skyscraper. Pile foundations are usually adopted for high rise buildings and when it is combined with raft slab they ensure that the problems of differential settlement are taken care of. In this paper the scenario of designing a skyscraper in seismic zone that is prone to earthquakes and the ground condition is such that it is located in vicinity of sea. Andaman and Nicobar isle is one similar place it falls under Zone V as per Indian Standards, hence prone to seismic activity and since it is surrounded by Bay of Bengal and Andaman sea, when seismic activity occurs there is a high chance of soil liquefaction to occur hence proper structural designs should be embraced.

Keywords: Seismic resistance, Soil liquefaction, Pile, Skyscraper, Gated community, Composite columns, Aerocon blocks, Fire measures

I. INTRODUCTION

Andaman and Nicobar Islands are located in epicentre of Eurasian plate, Indian plate, Sunda plate and Australian plate making it a hotspot for earthquakes. The surface when subjected to even minimum shaking the longer duration combined with shallow depth of water table causes soil liquefaction. When earthquake struck the isle on 26 December 2004 it turned out to be catastrophic resulting in lot of causalities what was noticed that the wooden buildings withstood the massive quake whereas the RCC structures collapsed and took heavy damage. The buildings along the periphery of Port Blair were constructed on slope and significant sliding of the structure about 50-70 mm were noted. The RCC buildings in central areas suffered settlements invariably due to erosion of soil by tsunami, failure of foundation, liquefaction of underlying soil and due to the fact that buildings were constructed without sufficient space between them for lateral deformations it resulted in pounding of building.

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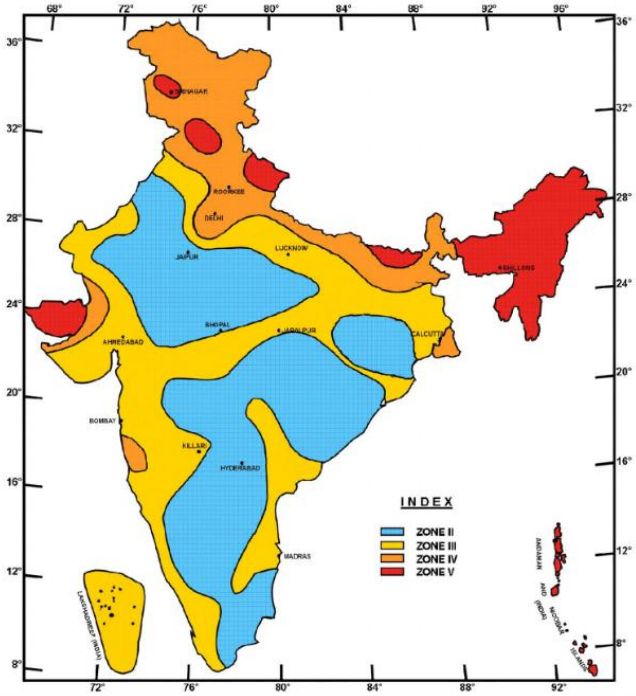

Fig 1: Seismic zones in India

Katchal and Kamotra island were the ones to get the most damage followed by Car Nicobar isle. Proper design techniques should be used in the construction of RCC buildings to withstand quakes and to avoid failure of foundation. The building should also have built in such a way that it resists uplift due to hydrostatic pressure.

II. PILE FOUNDATION

Pile foundations are capable of transferring heavy loads from the superstructure to greater depths when the soil right below the structure is incapable of taking those loads. Pile foundations are adopted in skyscrapers, dams, and bridges. When there is a layer of liquefiable soil beneath the structure the piles should be driven deeper past the liquefiable layer to hard rock layer below or a non-liquefiable crust. Multi-layered soil profile as in Andaman should be ensured the piles are safely driven in the hard rock that is available from depths varying from ten to fifteen meters rather than letting it as friction piles in the liquefiable soil layer which is dangerous for the structure.

Fig 2: Differential settlement due to liquefaction

Soil liquefaction is a phenomenon in which a cohesion less soil gets fully saturated due to presence of water source and then its starts to behave as a viscous liquid losing its bearing capacity, causing differential settlement results in overturning of the structure. When water logged soil is subjected to seismic activity the problems are escalated, the water molecules occupying the voids collapse forming a watery matrix and the soil particles are allowed to move freely making the soil lose its capacity to bear loads and heavy weight objects like buildings collapse due to the loss of the support beneath foundation.

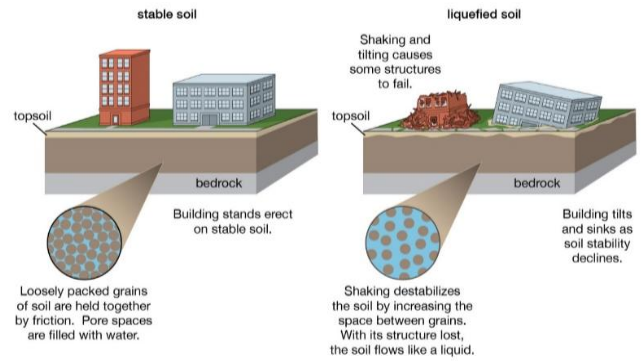

Fig 3: Phenomenon of soil liquefaction

The different soil profile cases and pile foundation in the isle are depicted in the below picture. In case 1&2 the pile will lose its resistance due to soil liquefaction and will settle but collapse will be avoided if the piles are embedded deep enough into hard layer. In case 3&4 the piles rest on soil layer that undergoes liquefaction hence failure of the structure is inevitable.

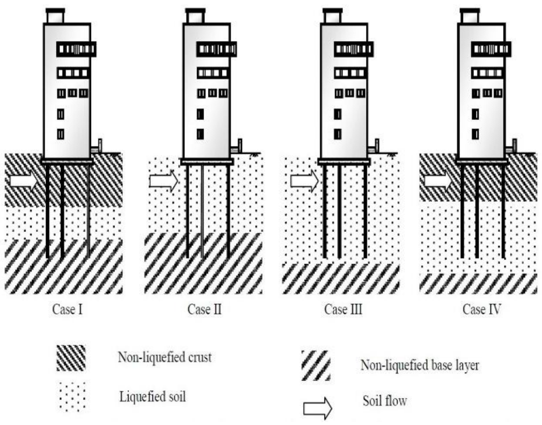

Fig 4: Soil Profiles and Pile foundation

III. PLAN

The plan is designed for an area of fifty square meter.There are total of forty stories with each storey built at height of 3.7 metre. The total elevation of the building is 145.3 metres .The carpet area for each house is 180 sq meter. The apartment is built as as a gated community

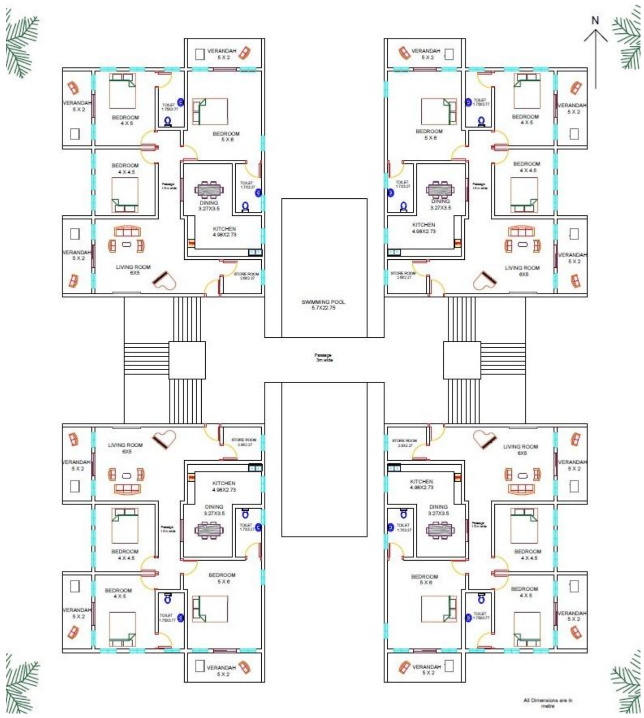

Fig 5: Floor plan of the Skyscraper

A. Gated Community

A gated community is a residential group of people who live within an system of their own fulfilling their own needs.It is for people who fancy quiet and peaceful life with all the modern facilities at their disposal.There are various benefits of gated community as follows

Safety & Privacy:

Safety and security is the first and foremost thing that comes into mind when Gated community is referred to, the houses are well guarded all through the day through security personal and through 24x7 video surveillance. Following safety is the extra privacy that gated communities give. Only the residents of the building along with guest are allowed inside the campus. It keeps the residents away from hustle and trespassers. This is one of the key advantage that makes people and public figures to prefer gated communities

Community circle:

Apart from safety and privacy the next beautiful thing living in a gated community is the presence of understanding between the residents , where they have their own togetherness in celebrations on festive occasions and hold parties now and then. There is familiarity between the residents and mutual respect and trust among them.

Lifestyle:

Gated communities have their own amenities within the compound itself from the basic medical facilities to the extravagant clubs for recreational purpose. Some of the common facilities usually available are tennis & shuttle courts, cricket & football pitches, swimming pools ,parks and kids care. The standout stuff is that residents get all these at a cost way lower than what they have to spend when they are living in individual houses where they have to pay exorbitant money. Comfortable living is ensured in a gated community.

Vehicular dangers:

Gated communities are kept away from speeding vehicles and traffic as they have their very own roads just for the inhabitants. The noise and pollution associated with vehicles wont bother the residents inside the gated community.Peace and quiet environment is provided for the resident. Absence of open roads and fast moving traffic ensures the safety of kids and they can play freely and safety of kids are ensured as there are no strangers inside and its easy for parents to monitor the kids.

Greener Environment:

Gated communities have abundance of flora and fauna within them and regular maintenance of the building ensures that plethora of fresh air is there for taking. Some gated communities use solar energy and rain water harvesting which can help the residents save a lot of money on their electric and water bills.

IV. DESIGN AND ANALYSIS OF SUPERSTRUCTURE

A. Composite column:

The design of skyscrapers requires new innovations in science and engineering this is where the concept of composite columns came into existence. The composite column exploits the characteristics of steel and concrete making the structure highly efficient by reducing the cross sectional area needed to bear the loads and also making the structure lightweight. Size of the column increases notoriously above one meter in width nowadays to withstand the heavy loads of high rise building, composite columns are the breakthrough for such problems. The two types of composite columns are as follows

1.Concrete filled section:

1.1 Rectangular filled steel tube:

A rectangular casing of steel is provided and infilled with concrete.

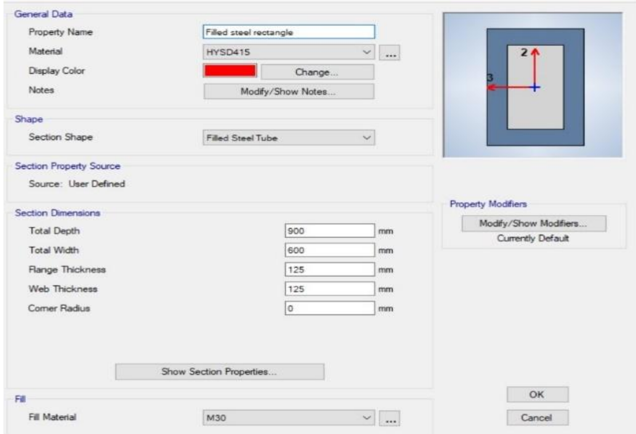

Fig 6: Rectangle steel tube

1.2 Square filled steel tube:

Square tube of steel is used to enclose concrete mass in its center.

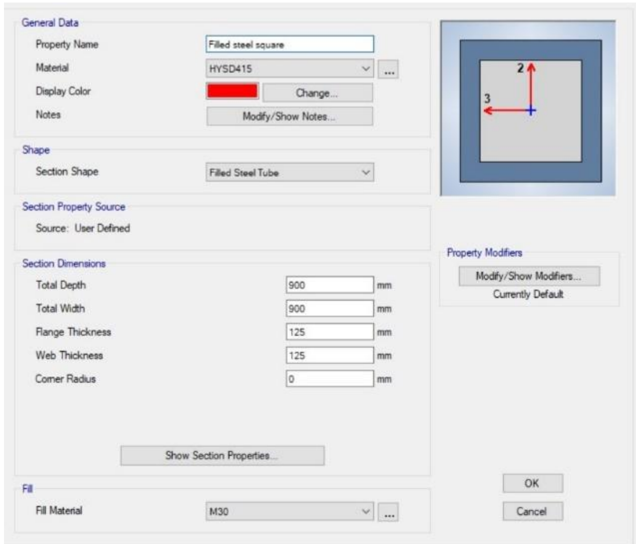

Fig 7: Square steel tube

1.3 Circular steel filled tube:

Circular concrete column in encased within a circular steel section

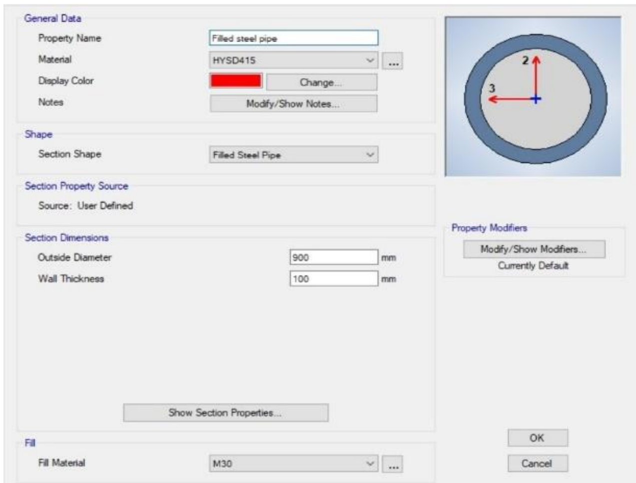

Fig 8: Filled steel pipe

2. Concrete encasement section:

2.1 Total encased rectangular section:

A rectangular section of concrete is centered by a steel I-section in the middle with at least two rebars at the corners of the concrete

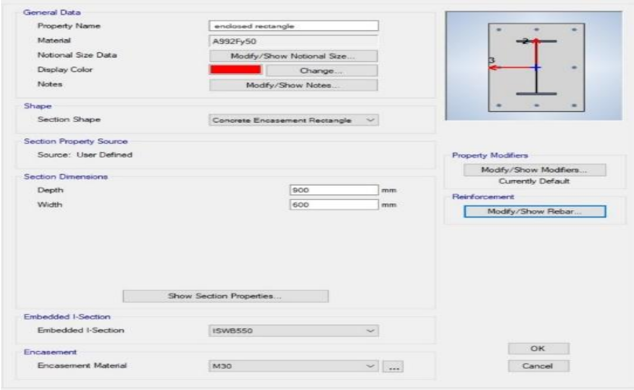

Fig 9: Total encased rectangular section

2.2 Total encased circular section:

An I-steel section is enclosed by circular concrete mass with rebars around the circumference of the steel section

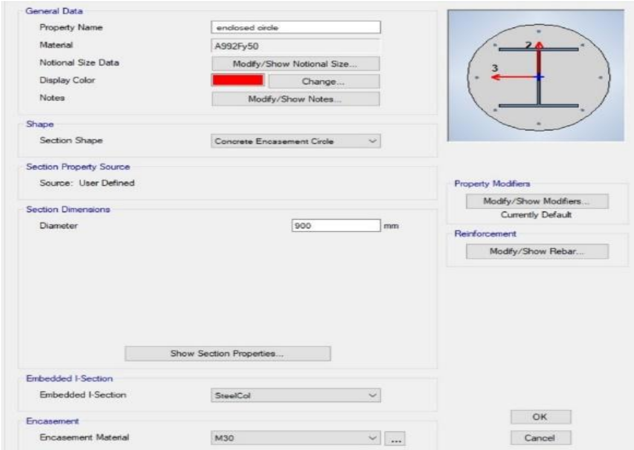

Fig 10: Total encased circular section

2.3 Partially encased rectangular section:

Concrete mass is present on either side of the I-steel section and the outer surface of the flanges are exposed. Rebars are provided on either side of the web.

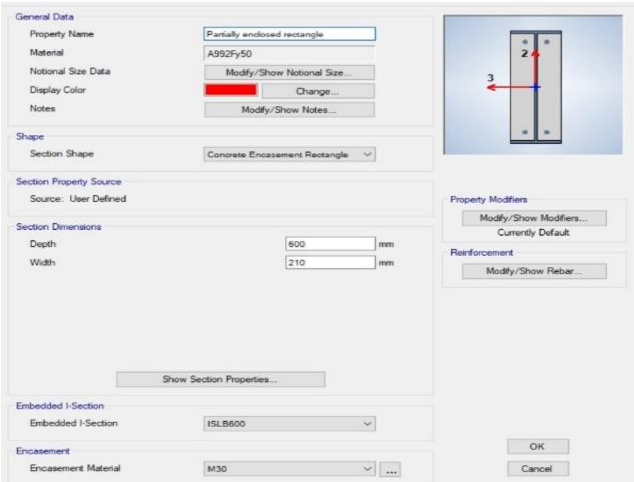

Fig 11: Partially encased rectangular section

B. Autoclaved aerated concrete blocks :

When it comes to high rise buildings one of the key aspects of design is to remove unwanted additional dead loads. Wall loads acting on frames is one such aspect. The traditional bricks with dry density of around 2000kg/m^3 imposes a load of around 11-15KN/m on the frames of the structure. AAC blocks are lightweight blocks with dimensions 600x150x150 mm has a dry density of 450kg/m^3 to 1000 kg/m^3 which is drastically less than conventional bricks, also the fact that AAC blocks are three times the size of one brick which in term means less mortar is required for bonding as the number of connections is reduced.The AAC blocks has a compressive strength of 4.5 N/mm^2 compared to bricks which has a maximum compressive strength of 3.5N/mm^2. AAC blocks are superb fire resisting material that can withstand fires upto a duration of four hours. Fly ash is the main composition of AAC block and hence the thermal conductivity of AAC block is very low and it ranges from 0.21W/mk to 0.42W/mk. For high rise building this property acts an an insulation layer for extreme external weather conditions. The resistance that AAC block has towards moisture is greater than red bricks. AAC blocks being porous in nature has excellent acoustics. They are termite resistance and have longer lifespan. AAC blocks reduce the steel needed by around 15% and the concrete needed by 7%. Seismic forces acting upon a building depends upon the dead load of the building so reducing the frame loads caused due to walls on each beams coupling it with the number of storeys invariably reduces the seismic load acting on the structure due to tectonic activity

V. METHODOLOGY

A. Seismic loads as per IS 1893

When it comes to design of concrete structures the following load combinations are adopted in design

- 1.5 (DL+LL)
- 1.2 (DL+LL±EL)
- 1.5 (DL±EL)
- 0.9 DL±1.5 EL

1.Seismic weight of floor:

The seismic weight of each floor is calculated as the sum of full dead load plus 25% of live load that is imposed if live load is less than or equal to 3 KN/m^2 or 50% of live load imposed if live load is greater than 3 KN/m^2 .Apart from this the combined weight of walls and columns in a storey should be evenly distributed to the top and bottom successive floors.

2. Seismic weight of building (Ws):

The summation of the seismic weight of individual floors will give the seismic weight of the building.

3. Calculation of base shear:

- $V_B = A_h .W_s$

Where A_h is design horizontal seismic coefficient which is calculated as

- $A_h = \frac{Z.I.Sa}{2.R.g}$

where Z is the zone factor and for very severe exposure the value of the zone factor corresponding to Zone V is 0.36

I is the Importance factor depending upon the purpose of the building for multistorey buildings the value of I should not be less than one.

S_a/g is the average response acceleration coefficient which is based upon the soil profile

R is the Response reduction factor based upon the ductility and brittleness of the structure. It should be noted that the ratio of Importance factor to Response reduction factor should not be greater than one

4. Distribution of Design Force:

The total force acting on the base of the structure is computed as base shear of the structure, which is then distributed to the entire structure. It is calculated by the following equation:

- $Q_i = \frac{Wi.hi^2}{\sum_{j=1}^{n} Wj.hj^2}$

Where Q_i = Design lateral force at floor i,

W_i = Seismic weight of floor i,

h_i = Height of floor i measured from base

n = Number of storeys in building

B. Analysis by ETABS:

The model is designed and analysed by using ETABS and the corresponding moments, shear forces, and axial forces acting on the structural components are found out. Totally encased rectangular composite column of 900 x 900mm in size is used for this skyscraper. Slabs of thickness 150 mm and beams are used as per the span requirement. M50 grade of concrete is used for column, M30 for beams and M25 for slabs.

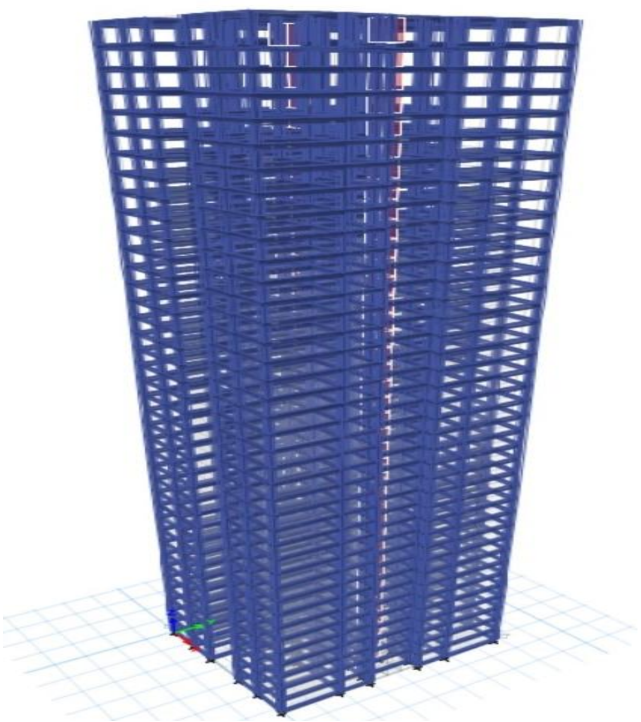

Fig 12: Modelling of skyscraper

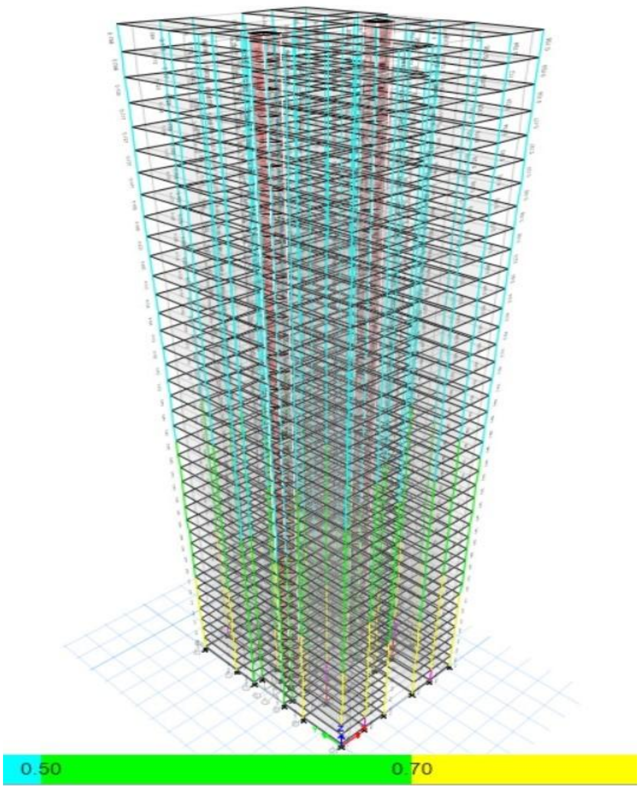

Fig 13: Composite column design

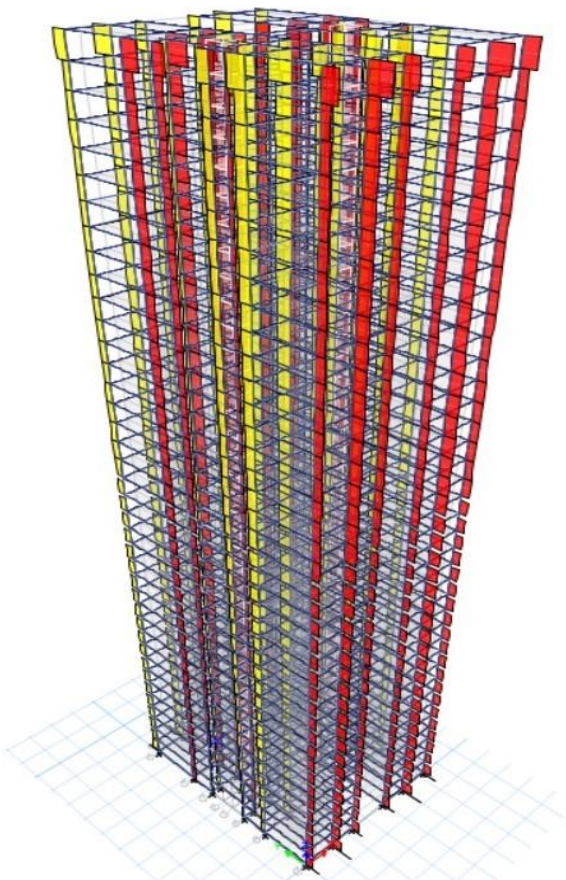

Fig 14: Shear force on columns

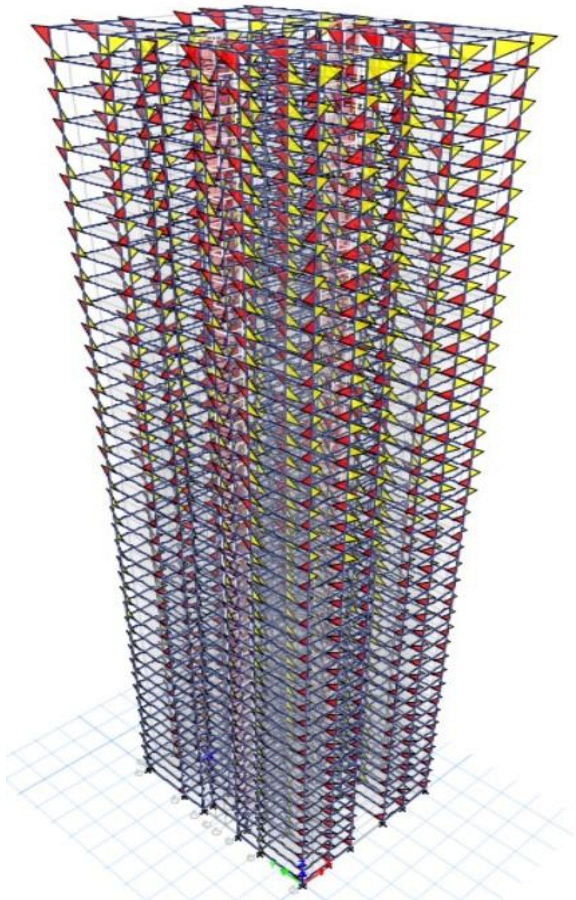

Fig 15: Bending moment on columns

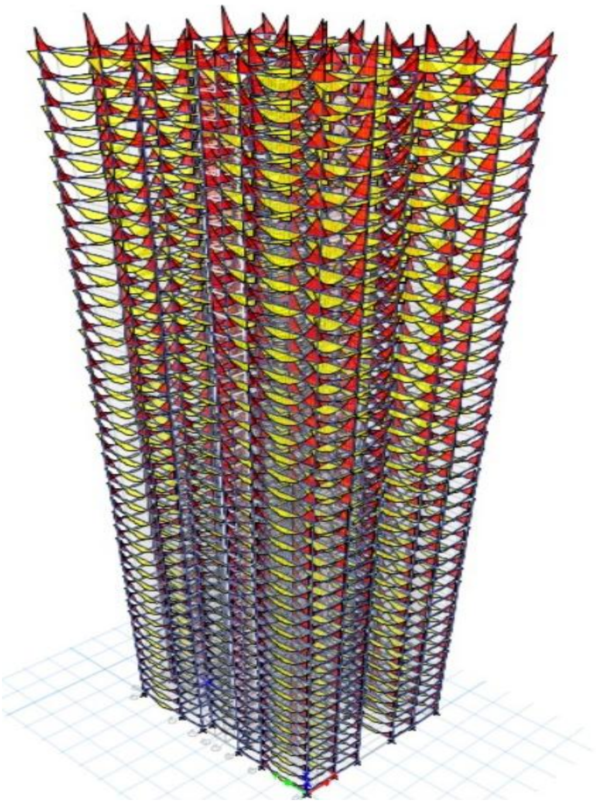

Fig 17: Bending moment on beams

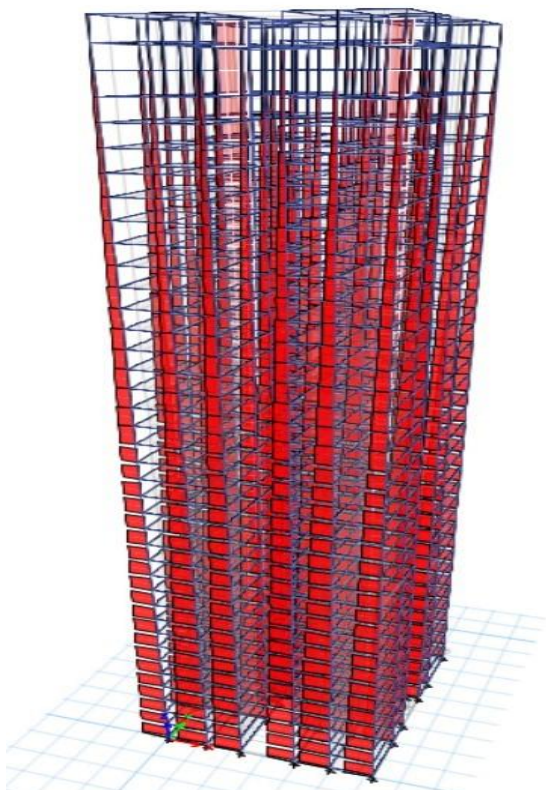

Fig 16:Axial forces on column

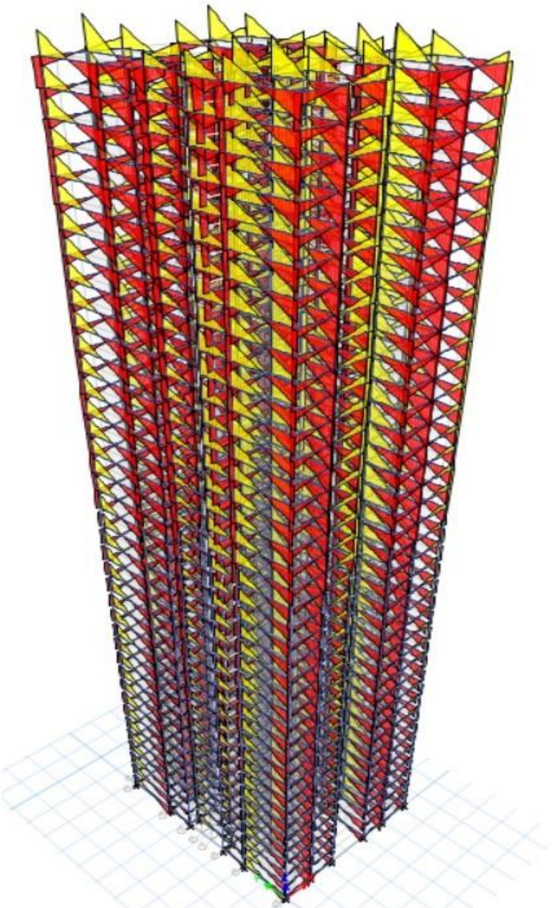

Fig 18: Shear force in beam

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C. Design of substructure:

SAFE software is used to design the foundation of the skyscraper. The foundation is designed as piled raft foundation the superstructure rests on a 3.8 m thick raft slab supported by piles, the piles are designed at a depth beyond the hard strata to avoid the phenomenon of liquefaction.

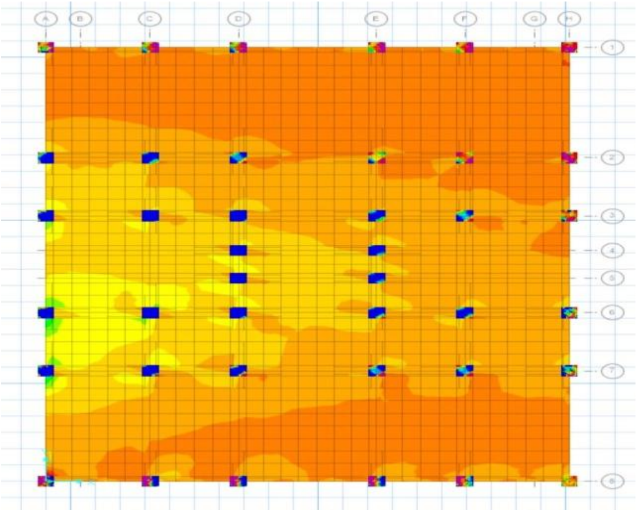

Fig 19: Deformed view

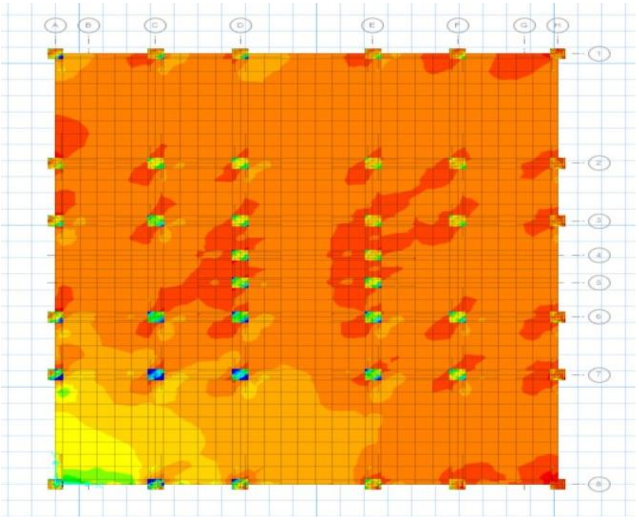

Fig 20:Maximum moment on foundation

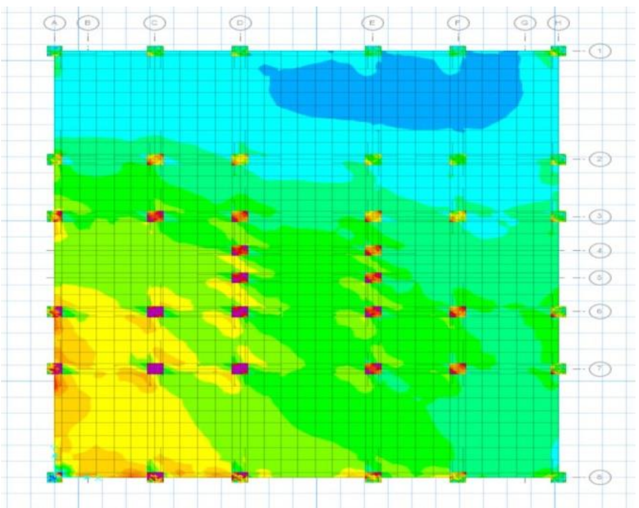

Fig 21: Minimum moment on foundation

Andaman and Nicobar island consist of sandy loams in most areas that undergo liquefaction and some parts are consisted of clayey loams that undergo strain softening effect. From analysis it is found out that that deeper the piles less the settlement and more the capability to withstand seismic forces. However increasing the thickness of raft slab didn't play much of role in reducing the settlement hence it is not adviceable rather increasing the depth of piles is more efficient in handling the problems related to earthquakes and differential settlement.

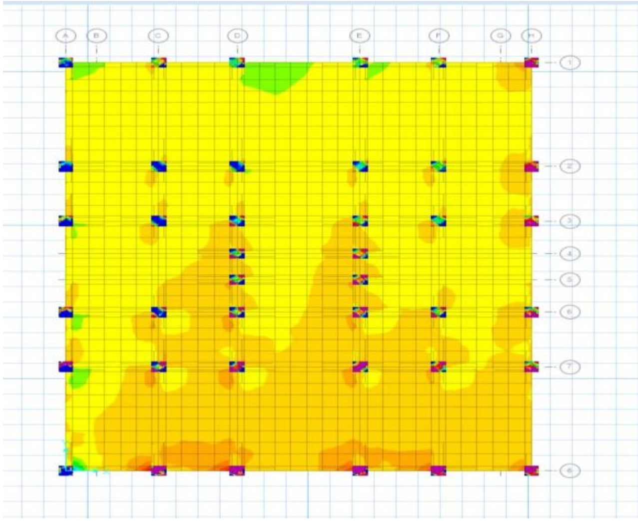

Fig 22: Shear force acting on top of Raft slab

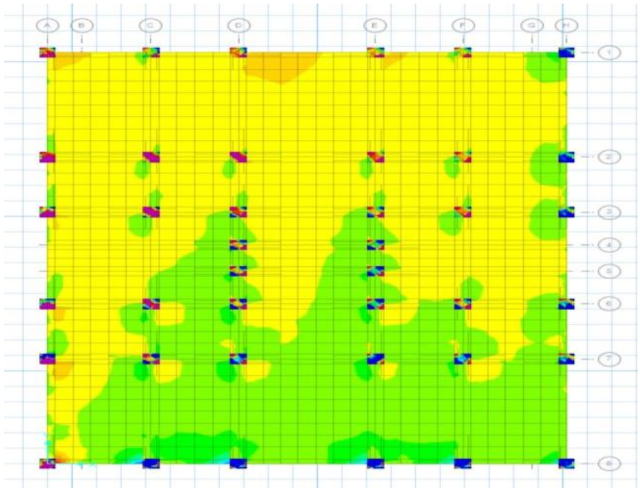

Fig 23: Shear force on bottom of Raft slab

VI. FIRE SAFETY MEASURES

There are many challenges in ensuring fire safety measures in a tall structure , the bigger problem is that the water hoses used by fire fighters can spray only till height of upto fifteen metres and skyscrapers are built over height of hundred meters, so the fire fighting crew has to enter the building through stairs all the way up the structure by that time there chances for fire to rapidly spread across successive floors.

To tackle these challenges fire compartmentation strategy is employed.

The structure is built with fire proof doors and barriers at all floors once the occupants of the floor ablaze are evacuated the barriers automatically shuts down and prevents spread of fire. The key aspect is that fire should burn itself out without causing the structure to collapse.

Apart from this a lift and stair is designed as fire lift and fire staircase. Underground water tanks with large capacities are built for immediate access of water during fire outbreak. Internal fire hydrants should be provided across all floors to aid the fire fighters. External fire hydrants should also be provided along the ground floor to control external flames. Generators should be provided to avert complications in case power lines are damaged due to fire. Smoke detectors are to be installed throughout the building and they should respond to onset of visible or invisible combustion particles. Automatic sprinkler systems should be provided with sensors that detect temperature changes and when activated should discharge jet of water to put off the flames.

The two key parameters to be taken into foreplay for fire design is the Available safe egress time and Required safe egress time. Available safe egress time is the time from onset of flames till the time the flame has adverse effects such as visibility geting reduced below ten meter, temperature getting elevated above sixty degree Celcius and the concentration of carbon monoxide suspended in air exceeding 1400 ppm. Required safe egress time is the time from when alarm sets off and the occupants in the building can safely evacuate the burning structure. Depending upon the height of the building the Available safe egress time should should be greater than that of Required safe egress time. The factor of safety of each structure varies according to its fire protection measures at disposal during times of emergency, a well equipped structure with fire suppression systems can have lower ratios of Available safe egress time to Required safe egress time

VII. RESULT

A. Effect of raft thickness in settlement:

The thickness of the raft slab was increased by three hundred millimetres and the corresponding settlement was noted. It was found out that the increase in thickness of slab does not reduce the settlement to greater extent. Hence optimum size of raft slab should be adopted. The cost of construction of raft slab for an area of 1230 mm^2 and 300 mm thickness is high due to the usage of high grade M50 concrete and heavy reinforcements in the foundation, and the corresponding difference in settlement is very low, hence it is not economical and preferable to increase the size of the raft , rather alternate options such as increasing the depth of the pile and number of piles is tested and results are obtained. For 3.5 metre RCC slab the settlement was 14.1mm and for 4.7 metre slab the settlement was 13.73 mm

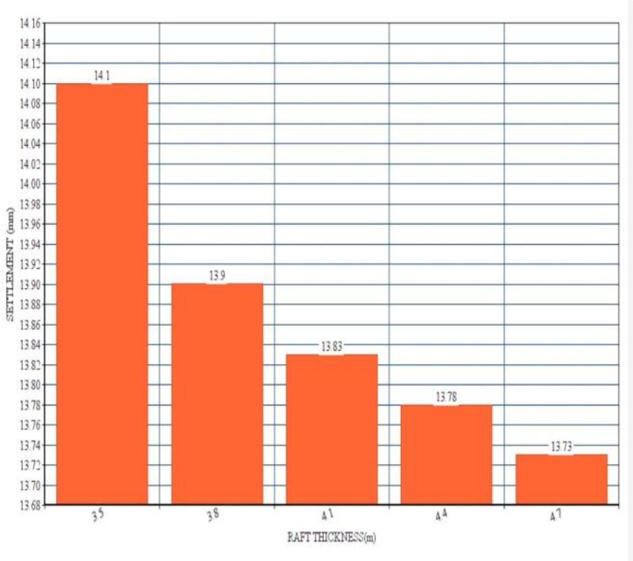

Fig 24: Effect of thickness of Raft slab

B. Effect of number of piles in settlement:

The number of piles in the raft foundation was increased by twenty each time and the corresponding settlement was noted, unlike the thickness of raft slab which didn't cause much of difference in settlement , the reduction in settlement was greatly improvised by increasing the number of piles. Piles of diameter six hundred and fifty milli meters were used and their corresponding settlement were found. The settlement was reduced from 15.23mm to 8.78 mm by increasing the number of piles from 200 to 280.

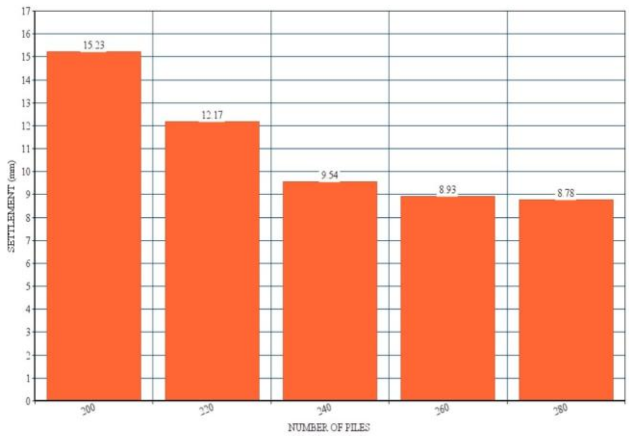

Fig 25: Effect of number of piles

C. Effect of depth of the piles in settlement:

Andaman and Nicobar islands have hard rocks present at depth of fifteen metres from mean sea level. The piles were driven at varying depths deep into the hard rock strata and their performance in settlement was noted down, considering hard rock strata is present at depth of fifteeen metres. Similar to number of piles the depth at which it is driven into the ground also significantly reduced the settlement caused. Settlements were reduced from 14.67 mm to 8.16 mm for depth of 25 m to 45m.

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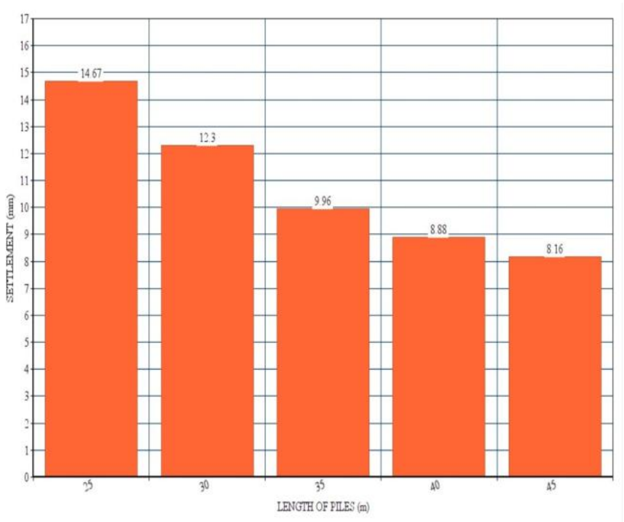

Fig 26: Effect of depth of piles

VIII. CONCLUSION

Increased population has been the main driving factor in increasing the requirement of skyscrapers, so proper execution techniques must be employed in construction to ensure safety of both the people working during construction to the ones living in it once it's put in occupancy. The soil conditions and location of water sources should be carefully analysed to ensure building doesn't undergo adverse changes in its composure. Safety measures should be given the highest priority in a skyscraper as lot of lives are put into stake during a calamity.

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