

Analysis and Design of Steam Turbine Generator Building with R.C.C. Deck

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ABSTRACT: Turbine generator or turbo-generator is the power generation machinery used in power plants. It is the most vital and expensive equipment of a power plant. The turbo-generator foundation consists of turbine, generator and its auxiliaries mounted on a R.C.C table top foundation which consists of top deck, columns and bottom raft. Heavy machinery with rotating masses requires a special support system that can resist the dynamic forces and resulting vibrations. A key ingredient to the successful foundation design for a turbo-generator is the careful engineering analysis of the foundation response to the dynamic loads from the anticipated operation of the machine. The paper presents a detailed procedure for the finite element modelling, static and dynamic analysis of the foundation structure. To demonstrate the analysis procedure model of turbo generator foundation of a plant in Kakinada, AP is done using software STAAD.Pro and design is carried out using excel spread sheets as per IS 2974 Part-III (1992).

KEYWORDS: Turbo-generator, Foundation, Finite element, Static and Dynamic analysis

I. INTRODUCTION

The growth of electricity consumption in the world is evolving with environmental requirements and it is expected that the fossil fuel price increases inspires the current production of renewable energy thermal combined with re-cycle power plants. Turbine-generator foundation is a complex engineering structural component. Different types of turbine foundation are used for different machines depending on their capacity, geometrical sizes and constructional features. Dynamic behaviour of the foundation plays an important role in providing normal operating conditions for the supported turbine-generator. In high seismic regions, seismic forces are extremely significant to be included as lateral load when designing the turbine foundation. The foundation not only should have a sufficient bearing capacity to support the turbine machine and its auxiliary equipment, but also be designed to limit the vibration amplitudes of the shaft, the rotors and the bearings within the acceptable level. Excessive vibration amplitudes and deflections may cause serious damage if rotor blades hit the casing. RC turbine-generator floor comprises of top deck, supporting structure and a raft foundation system. All the equipment of power plant including turbine, generator, governor and other mechanical-electrical instruments are located on top of the deck. This foundation consists of a raft directly resting on strong soil or resting on piles if the soil is soft. The different types of foundation are block type, combined block type, table top type, table top with isolators, spring type, inertia block and pile supported foundations. The frame type foundations are most popular because of saving in space, saving in materials, easy accessibility to all machine parts for inspection and less liability to cracking due to settlement and temperature changes. A frame type foundation is shown in Fig 1.

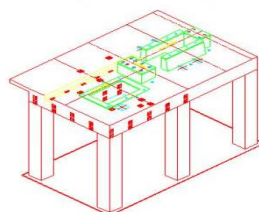


Fig. 1: Frame type foundation

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In the above Fig. the turbine will be placed in the cut-out, after that the turbine gearbox will be placed on the raised pedestal directly in front and generator will be placed on the last pedestal. The machines should be so placed that centre of gravity of all the machines are in one line. In the last two decades rapid advances in the techniques for design of engineering structures have been made. With this much progress it is surprising that mathematical modelling and experimental dynamic investigations of elevated foundations supporting vibration machinery has hardly progressed. The main factors contributing to this situation are the tendency for equipment manufacturers to rely on past successful practices, the lack of interest in academic circles for this type of engineering structures and the lack of funds for major studies. While the importance of the dynamic analysis of turbogenerator foundations has been a known fact for many years the study of bibliography shows that research results in this field are far from being satisfactory.

In this paper finite element model of a turbo-generator deck has been prepared using software STAAD.Pro. There are many ways of representing the model of a frame foundation using beam elements, shell elements, solid elements or a combination of all of these each with its associated limitations. The obvious choice for the super structure is to model it as a space frame where the beams and columns are idealized as beam elements having six degrees of freedom at each node.

Jayarajan P. & Kouzer K. M.^[1], studied the finite element modelling of foundation structure to demonstrate the analysis procedures using SAP2000. They conclude that dynamic analysis of turbine foundation needs attention to detail both in modelling as well as interpretation of results. They highlight the various issues related to mathematical modelling of structure, machine and soil for dynamic analysis of the foundation. P. St. Fleischer & P. G. Trombik^[3], propose simplified design principles for large machine foundations and specific requirements for turbo generators which are sometimes in contradiction to seismic design demands. According to them soil-structure-interaction is an eminent attribute, as first Eigen frequencies are in strong dependence to the bedding situation, and are often situated within the critical earthquake frequency range. Peter Nawrotzki, Gunter Huffman et al.^[4], present a systematic overview of the static and dynamic analysis of turbine foundations made of reinforced concrete. It discusses the load cases to be applied, the required ultimate limit and serviceability limit state checks, the assessment of the static and dynamic foundation stiffness and special provisions in seismic areas. Shafii Abdullah, Nor Hayati et al.^[5], designed a rigid-moment frame supporting the turbine-generator according to BS 8110. This structure was subjected to vibrations of turbine-generators and seismic loading. Turbine-generator with its foundation was modelled as single degree of freedom (SDOF) using RUAUMOKO program. The result shows that turbine foundation under Imperial Valley earthquake does not exceed yield drift limit for monolithic connection and remains within the elastic condition. Contradictorily, turbine foundation exceeds yield drift limit under San Fernando earthquake loading and is likely to collapse. Sukanta Adhikari^[8], deals with the design of a turbo generator foundation for a thermal power plant. The paper covers the critical aspect in design of turbo generator foundation with respect to IS 2974 (Part 3)-1992 and other international standards. Fang Ming, Wang Tao et al.^[14], in this paper a 1000 MW turbine-foundation-soil system is analysed under excitations from rotor unbalances and earthquakes. The influence of soil-structure interaction (SSI) on the response of the system is explored by using three-dimensional viscous-spring boundary elements. It is found that the effect of SSI strongly influences the displacements and internal forces of the system under rotor unbalance excitation.

In this study three models have been prepared, two top deck models and one bottom raft model as shown in Fig 2. and Fig 3. Dynamic time history analysis has been performed for finding out the natural frequency of vibration and for checking the maximum amplitude of vibration. After that static analysis has been performed on both deck and raft model to check the strength and accordingly carry out the design. Top deck beams, columns and bottom raft have been designed based on the analysis results from STAAD.Pro models using excel spreadsheets. Detailed drawings have been prepared in AutoCAD. Paper is organized as follows. Section II describes methodology. Section III gives theoretical formulation, which involves various theories and formulas to be used in this project. Section IV presents various results obtained. Finally, Section V presents conclusion.

II. METHODOLOGY

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The methodology includes modelling of the turbo generator foundation as a space frame where top deck beams and columns are idealised as beam elements using STAAD.Pro software. Dynamic analysis on the model has been performed to find the natural frequency of the foundation in all three directions along with maximum amplitude of vibration in horizontal and vertical directions. The results obtained have been checked with codal provisions and manufacturer standards. Static analysis has been performed on the same model and design of top deck beams and columns has been carried out using the results of this analysis. Modelling of the raft has been done by idealising it as plate bending elements supported on piles. Piles have been considered as fixed-but supports with stiffness's in horizontal and vertical directions. Static analysis has been performed on it using the same load cases and combinations as previous one and design of the various structural components is done using excel spread sheets. Detailed drawings have been drawn in AutoCAD.

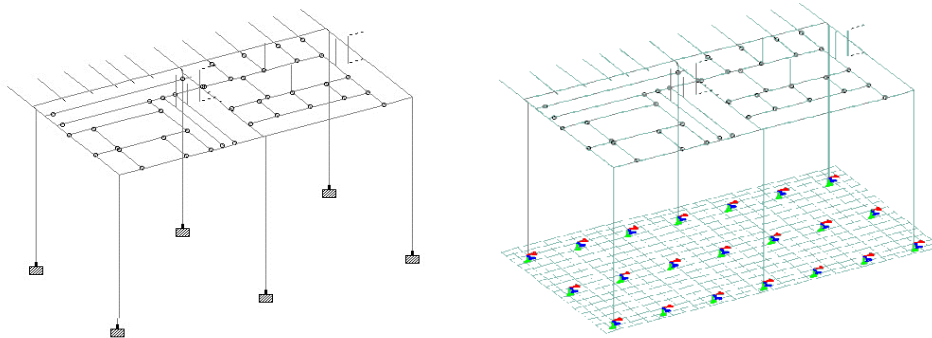


Fig. 2: Top deck beam model Fig. 3: Bottom raft model

Fig. 2 shows the STAAD.Pro model of top deck of foundation in which beams and columns are idealized as beam elements and the extended cantilever projections is the walkway. Fig. 3 shows the bottom raft model in which plate elements are used for modelling of raft and piles are idealised as fixed-but supports.

III. THEORETICAL FORMULATION

(1) Dynamic Analysis Formulation:

Due to unsatisfactory balancing of rotating parts in practice the mass centroid of rotating part does not coincide with center of rotation. In the course of operation the initial defective balancing may be increased at an alarming rate in consequence of the loosening, corrosion or breakage of the turbine blades. Also the defects of the lubrication system, deficiency of the packing and uneven warming up of rotating parts may cause expansion resulting in vibrations which do not follow simple harmonic motion. Thus unbalancing forces are produced of the form, $F(t) = F_0 \sin(\omega t + \phi)$ as shown in Fig. 4 below.

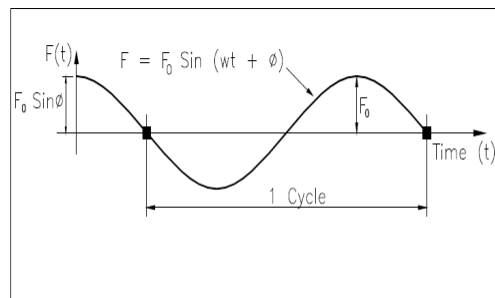


Fig. 4

$$F_0 = (m\omega^2) \times \text{F.O.S.}$$

Where,

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m- Mass of rotor, e- Eccentricity in mm, ω – Operating speed of machine (turbine or generator) in radian/sec
F.O.S- Fatigue factor is taken as 2 as per IS 2974 (part3):1992

The eccentricity of rotor mass can be obtained from,

$$G=e\omega$$

Where, G – Balance quality grade in mm/s (refer ISO 1940)

The unbalance forces obtained as per the above formula for turbine and generator are then entered as harmonic forces in STAAD Pro. for doing the time history analysis.

(2) Static Analysis Formulation:

Primary load cases taken for static analysis are:

- (i) Dead load(ii) Live load(iii) Static load(iv) Static torque load(v) Loss of blade circulation +ve
- (vi) Loss of blade circulation –ve (vii) Thermal expansion load (viii) Dynamic load +ve (ix) Dynamic load –ve
- (x) Short circuit load +ve (xi) Short circuit load –ve (xii) Temperature load (xiii) Shrinkage load (xiv) Seismic X
- (xv) Seismic Z

Load combinations considered were:

Normal condition

DL + LL + SL

Operating condition

DL + LL + OL + TLF/SHRK

Short circuit condition

DL + LL + OL + TLF/SHRK + SCF (+ve and –ve)

Loss of blade condition

DL + LL + OL + TLF/SHRK + LBL (+ve and –ve)

Seismic condition

DL + OL + TLF/SHRK + EQL

Where,

DL Dead Loads

LL Live Loads

SL Static Loads (including static load and static torque load)

OL OperatingLoads (including thermal expansion load, static loads, dynamic loads)

LBL Loss of Blade condition

TLF Temperature Loads

SCF Short circuit Loads

SHRK Shrinkage Loads

EQL Seismic Loads

Dead load includes self-weight of the foundation as well as weight of machines and its auxiliaries. Self-weight of top deck and columns is applied using self-weight command in STAAD.Pro. Live load was taken as 15 kN/m² on each beam. Static loads, operating loads, loss of blade condition loads, short circuit loads were taken according to manufacturer's specifications. Temperature load was taken considering temperature difference of 50⁰C between top deck and bottom raft. To account for the Shrinkage of the upper deck slab relative to the base a temperature difference of 10⁰C has been considered. For design of top deck beams M_z , M_y and torsion results from software were taken and entered in excel spread sheets. Working stress method was used for design. Same load cases and combinations were used in static analysis of raft. Thickness of raft was 1.6 m and was supported on 500 mm dia piles. For longitudinal reinforcement in top deck,

Equivalent bending moment, $M_{ze} = M_z + M_t$

$$M_t = T (1 + D/b)/1.7$$

The following interaction equation should be satisfied

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$$\frac{M_{ze} + M_y}{M_{ze1} M_y} < 1$$

For shear, Equivalent shear, $V_C = (V + 1.6 T/b)$

Raft design:

For raft model the value of stiffness in horizontal and vertical directions for pile fixed but supports was calculated using below formulae

Vertical stiffness (K_z)

$$K_z = (EA/r_o) F_{18.1}$$

Horizontal stiffness (K_h)

$$K_h = (EI/r_o^3) F_{11.1}$$

Where,

E---- Dynamic modulus of elasticity of pile

A---- Area of c/s of pile

Ro--- eff. radius of pile

$F_{18.1}$ --- Novak's f_{ji}

V_s --- Shear wave velocity of soil

V_p --- Shear wave velocity of pile

$$V_s = \sqrt{G/\gamma_s}$$

$$V_p = \sqrt{E_p/\gamma_p}$$

Raft was designed using working stress method. The results are shown in tables below

IV. RESULTS

The natural frequencies of the foundation in all three directions were obtained by doing time history analysis in STAAD pro. The results are shown in table no 1 below.

Table no.1: Frequency summary

Equipment	Condition	Speed	Natural frequency of the foundation in Z direction	Ratio	Natural frequency of the foundation in X direction	Ratio	Natural frequency of the foundation in Y direction	Ratio
		fm rpm	fn rpm	fn / fm	fn rpm	fn / fm	fn rpm	fn / fm
TURBINE	Operating Speed	10800	386.7	0.036	389.94	0.036	1162.2	0.108
GENERATOR	Operating Speed	1500		0.26		0.26		0.775

According to IS 2974(Part3):1992 the fundamental natural frequency shall be at least 20 percent away from the machine operating speed that is, $f_n < 0.8f_m$ or $f_n > 1.2f_m$. From the above table it can be seen that the conditions are satisfied everywhere. Apart from these the maximum amplitude of vibration of the foundation should be less than the limits specified by the manufacturer. Table no 2 shows the amplitudes of vibration in both horizontal and vertical directions.

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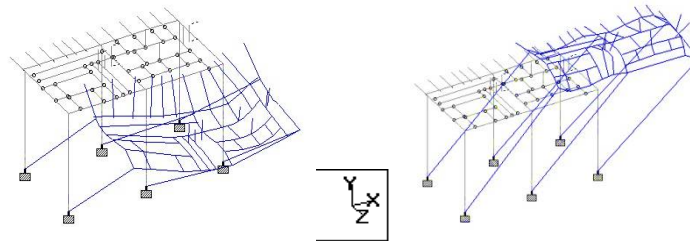
Table no.2: Amplitude summary

S.no.	Cases	Amplitude of Vibration in mm					
		Turbine Side			Generator Side		
		Amp from STAAD	Permissible amp	Remarks	Amp from STAAD	Permissible amp	Remarks
1	AM-Y-R	0.003	0.04	O.K.	0.003	0.06	O.K.
2	AM-Z-R	0.002	0.05	O.K.	0.001	0.09	O.K.

The basic goal in the design of a machine foundation is to limit its motion to amplitudes that neither endanger the satisfactory operation of the machine nor disturb people working in the immediate vicinity. In above table maximum amplitudes of the machines in their areas of influence was obtained by doing dynamic time history analysis in software STAAD.Pro and compared with manufacturer's specifications. In all cases conditions were found to be satisfied.

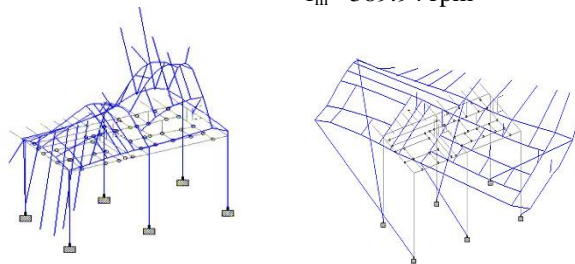
Mode shapes:

The fundamental mode shapes in all three directions along with their participation factors and corresponding frequencies are shown in Fig 5. below.



(a) Mode shape 1 (97.93%),
 $f_m = 386.7$ rpm

(b) Mode shape 2 (98.82%),
 $f_m = 389.94$ rpm



(c) Mode shape 6 (50.09%),
 $f_m = 1162.2$ rpm

(d) Mode shape 3, $f_m = 554.3$ rpm

Fig 5. Mode shapes

In the above Fig. mode 1 shows predominantly translation in Z-direction, mode 2 in X-direction, mode 6 in Y-direction and mode 3 is torsional mode. It is found that frequency in Y-direction i.e. mode shape 6 is the most critical one.

(II) Results of static analysis

The top deck beams should have reinforcement according to provisions of IS 2974(part 3):1992 given below:

Top and bottom: 0.25 percent (each) of gross sectional area.

Sides: 0.1 percent gross sectional area on each side.

Beam layout has been shown in Fig. No 6. The details of the various beams have been shown in Table No.3

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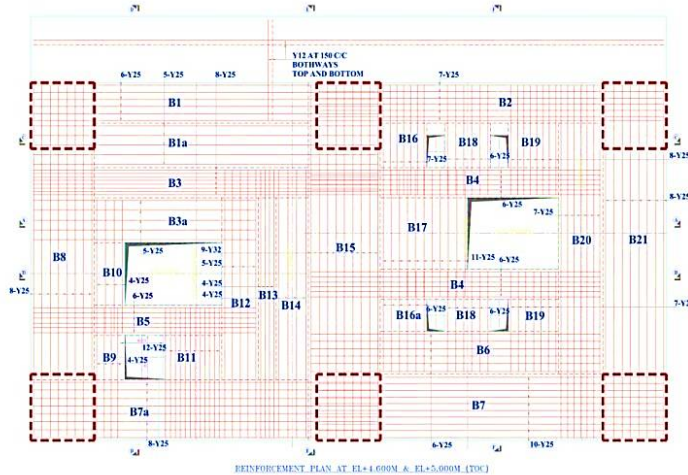


Fig 6 Top deck beam layout

In the above Fig. red lines are the reinforcement. The square shapes with dotted lines represent the columns. The blue text shows the beam mark. The details of these beams are shown in Table No. 3

Table No. 3 Beam design results

Beam No.	Beam size	Top bar	Bottom bar	Side face	Stirrups
B ₁	739 x 1250	6#25	6#25	4#25	6 lggd 10# @ 250c/c
B ₂	739 x 1250	7#25	7#25	4#25	6 lggd 10# @ 200c/c
B ₃	550 x 850	8#25	8#25	3#20	4 lggd 10# @ 150c/c
B ₄	550 x 1250	6#25	6#25	3#25	4 lggd 10# @ 200c/c
B ₅	550 x 1250	6#25	6#25	4#20	4 lggd 10# @ 200c/c
B ₆	780 x 1250	6#25	6#25	3#25	6 lggd 10# @ 200c/c
B ₇	1200 x 1250	10#25	10#25	5#25	6 lggd 10# @ 125c/c
B ₈	1200 x 1250	8#25	8#25	5#25	6 lggd 10# @ 125c/c
B ₉	580 x 1250	7#20	7#20	4#20	4 lggd 10# @ 225c/c
B ₁₀	580 x 1250	4#25	4#25	2#25	4 lggd 10# @ 250c/c
B ₁₁	1115 x 1250	12#25	12#25	4#25	6 lggd 10# @ 150c/c
B ₁₂	660 x 1250	5#25	5#25	4#20	4 lggd 10# @ 200c/c
B ₁₃	320 x 1250	4#25	4#25	2#25	2 lggd 10# @ 250c/c
B ₁₄	580 x 1250	4#25	4#25	3#25	4 lggd 10# @ 250c/c
B ₁₅	1360 x 1250	9#32	9#32	5#32	6 lggd 10# @ 125c/c
B ₁₆	875 x 1250	7#25	7#25	4#25	4 lggd 10# @ 150c/c
B ₁₇	1645 x 1250	11#25	11#25	5#25	6 lggd 10# @ 125c/c
B ₁₈	860 x 1250	6#25	6#25	4#20	6 lggd 10# @ 200c/c
B ₁₉	948 x 1250	8#25	8#25	4#25	6 lggd 10# @ 200c/c
B ₂₀	837 x 1250	7#25	7#25	4#25	6 lggd 10# @ 250c/c
B ₂₁	1200 x 1250	8#25	8#25	4#25	6 lggd 10# @ 150c/c

All the beams above are designed for combined bending moment and torsion according to provisions of IS 456 using working stress method. They are also designed for combined shear and torsion. They are subjected to minimum reinforcement checks according to IS 2974(part 3):1992

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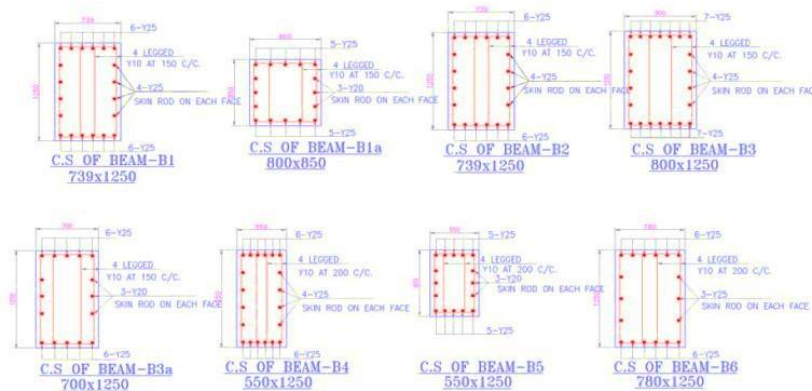


Fig 7 Top deck beam details

Above Fig. shows the cross sectional details of a few selected beams. The red dots represent the reinforcement rods and the vertical lines are the stirrups. All dimensions are in mm.

Results of static analysis of raft:

According to IS 2974(Part 3):1992 0.12 percent of gross sectional area in each direction should be the min reinforcement. Shrinkage reinforcement of 0.06 percent should be provided in each direction if the raft thickness is more than 2 m. Design is done using working stress method. For design max values of moment and shear among all the plate bending elements should be taken. The values of moment and shear are shown in Table No. 3

Table no.3: Summary of moments & Shear under operating condition

PLATE	L/C	Shear		Bending Moment			Design moment	
		SQX	SQY	M _x	M _y	M _{xy}	M _x + M _{xy}	M _y + M _{xy}
		KN / m ²	KN / m ²	KN-m	KN-m	KN-m	KN-m	KN-m
746	107	0.282	-0.306					
989	110	0.268	0.338					
329	123	-0.12	0.117	260.2	57	-5.9	266.1	62.9
1028	123	0.109	0.173	52.2	297.2	37.7	89.9	334.9
760	121	0.191	0.228	234.4	-22.8	286.04	520.44	308.84

From the above table, Maximum design moment = 520.44 KN-m, Maximum design shear Stress = 0.338 N/mm²
Using the above values, reinforcement required is 25#@150 c/c for top as well as bottom. The details of the raft are shown in Fig. 8. The raft is supported on piles of diameter 500 mm as soil profile at the site is marine silty clay which has very low bearing capacity. The load carrying capacity of each pile is 50 kg/cm² and length is 30 m. Spacing of each pile is 1.8 meters. The details of typical pile is shown in Fig. 9

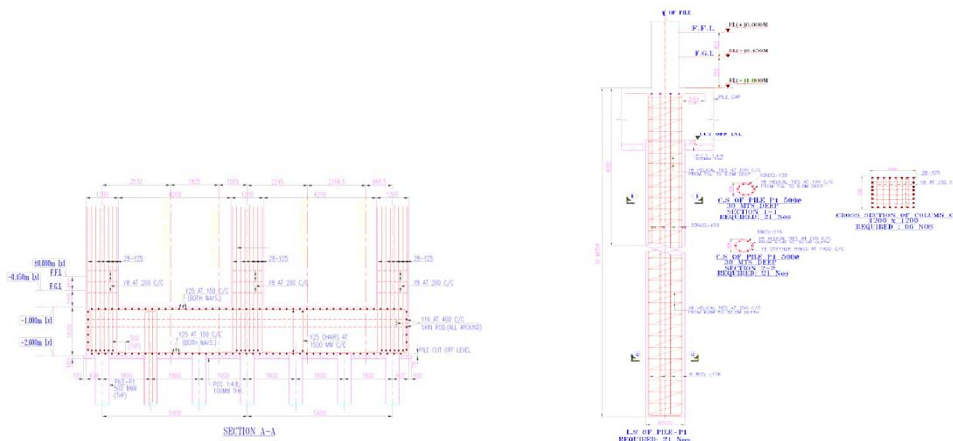


Fig 8 Bottom deck raft details

Fig 9 Pile foundation details

Fig. 8 shows the cross section of the bottom raft supported on piles. Reinforcement has been provided at both top as well as bottom and skin rods have been provided at 1500 mm c/c and column and pile reinforcement is shown extending into it. Fig. 9 shows the longitudinal as well as cross sectional view of the pile. The calculated percentage of reinforcement has been given only till fixity length of pile, for rest of the pile minimum amount of reinforcement has been given.

V. CONCLUSIONS

The RC turbine foundation has been successfully analyzed by time history method using STAAD.Pro. The natural frequency of the foundation is 386.7 rpm (Z-direction), 389.94 rpm (X-direction) and 1162.2 rpm (Y-direction) which is much lower than the operating frequencies of turbine and machine. Resonance condition can be avoided with good dimensioning and design of the various structural components. The amplitude of vibration of machine from STAAD.Pro for turbine and generator are within limits specified by manufacturer. The design of top deck beams and raft has been done according to IS 2974(part 3):1992 and it has been found that the dimensions of beams and base raft are ok. The drawings can be approved for construction.

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