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SYNOPSIS The paper reviews the current state of the art on the dynamic and static analyses of RCC space frames supporting high speed centrifugal machines e.g. large turbogenerators and compressors. The need to include the effects of soil-structure interaction formulations on overall behaviour of various analytical models are highlighted. At the same time, the uncertainties involved in evaluating essential geotechnical parameters and paucity of reliable and elaborate information from the machine manufacturers are discussed. The analysis and design aspects of this inter-disciplinary problem are illustrated with two typical design case studies selected from authors' own experience in this specialised field. The paper also discusses the usefulness, if any, of such rigorous analysis and identifies various shortcomings which still persist in finalising realistic design data and adopting suitable models to represent machine foundation-soil system.

INTRODUCTION

The rapid growth in industrialisation in recent years has necessitated the installation of heavy and complex machinery at various locations. The capacities of the machinery e.g. turbomachines, compressors and pumps have increased a great deal as also the sizes of their constituent units involved, calling for a modern analytical approach for their supporting structure.

All physical systems, built of material possessing mass and elasticity, are capable of vibrating at their own natural frequencies. Engineering structures, subjected to vibratory forces, experience vibration in different degrees and their design requires determination of their oscillatory behaviour. The current design office state of the art considers only their linear behaviour because of the convenience afforded by applying the principle of superposition, and also because the mathematical technique available for their treatment are well developed. In contrast, non-linear behaviour of systems is less well known in spite of the fact that all structures tend to behave nonlinearly at exceedingly high amplitudes of vibration. However, for reinforced concrete framed structures supporting high speed centrifugal machines, question of allowing high amplitude of vibration does not arise due to very stringent allowable design amplitude requirements put forward by various machine manufacturers.

Modeling of the real structure, machine and the supporting soil is of critical importance in obtaining results that will approach the actual performance of the combined soil-structure interactive system. Selection of non-realistic design parameters will also render these rigorous analysis appear meaningless. The link between the real structural system and the mathematically feasible solutions is provided by the mathematical model which is the symbolic designation for the substitute idealised system.

Some of the modern techniques are lumped parameter model analysis, soil-structure interaction, elastic half-space theory and the latest computer programs available to the designers. This paper highlights synthesis of present state of the are in the analysis and design of two framed foundations supporting a compressor and a turbogenerator respectively. A comprehensive analytical approach using four computer models of the two types of foundations under study are presented and discussed in this paper.

DESIGN CASE STUDIES

Extracts of computer solutions of two typical design case studies using computer software package SAP IV are furnished through Tables I to IV. These examples are selected to highlight the influence of soil-structure interaction and related design parameters pertaining to dynamic soil properties and the unbalanced forces of the machinery on the static stress analysis and dynamic response of the supporting reinforced concrete space frames.

Foundation Sizing

The trial dimensions of these two foundations are selected to meet respective machine manufacturer's basic guidelines viz. machine assembly and piping requirements and also to satisfy preliminary criteria under trial sizing of elevated foundations which are to check whether (1) thickness of the mat is adequate to assure its rigid behaviour; (2) centre of column resistance coincides with the centre of gravity of the equipments plus the top half of the structure (3) centre of resistance of the soil is found to coincide with the centroid of all superimposed loads i.e. structure plus machine (4) ratio of mass of structure to mass of machine is more than 2.5; (5) column and beam static deflections considering various combinations of static machine loads, creep, thermal

TABLE I Free Vibration Analysis of Compressor Foundation Models

Mode No.	Frequency (Cycles/sec)			Period (sec)		
	Model A_1	Model B_1	Model C_1	Model A_1	Model B_1	Model C_1
1st	7.19	1,46	1.36	0,14	0.686	0.743
2nd	8.55	2.26	1.91	0.117	0.443	0.523
3rd	9.92	2,89	2.09	0.101	0.346	0.477
4th	21.23	4.36	3.93	0.047	0.229	0.340
5th	28,74	4.70	3.00	0.035	0.212	0.333
10th	55,9	25.3	21.2	0.018	0.039	0.047
15th	73,9	49.13	49.15	0,013	0.020	0.023
20th	129.3	67.8	69.39	0,008	0.015	0.014

Note: Model B_1 is with base raft 1.0m thick.
Model C_1 is with base raft 3.0m thick.

TABLE II Static Stress Outputs of Typical Prismatic Beam Elements of Compressor Foundation Computer Models
Unit of force-KN, moment-KN metre

Element No.	Stress Component					
	Axial	Shear	Shear	Torsion	Moment	Moment
1 Model A_1	277,8	3.41	-1.8	0,04	3,95	5.9
	-277.8	-3.41	1.8	-0.04	5.13	11.8
Model B_1	288,1	-1,47	2,3	0.03	-7.94	-13,5
	-288,1	1,47	-2,3	-0,03	-3.88	5,9
9 Model A_1	21,73	-170,4	*	*	0.097	-86,13
	-21.73	170.4	*	*	-0,097	-173,8
Model B_1	14.23	-170,4	*	*	0.079	-80,1
	-14.23	170.4	*	*	-0,079	-180.2
10 Model A_1	21.73	170,4	*	*	0,097	173.8
	-21.73	-170,4	*	*	-0.097	86,13
Model B_1	14,23	170.4	*	*	0.079	180,2
	-14.23	-170.4	*	*	-0.079	80,1

* values are found to be negligible

TABLE III Free Vibration Analysis of Turbogenerator Foundation Models

Mode No.	Frequency (cycle/sec)		Period (sec)	
	Model A_2	Model B_2	Model A_2	Model B_2
1st	1,569	1.016	0.637	0,984
2nd	1,748	1,133	0.572	0.882
d	2,089	1.596	0.478	0,627
	5.737	5,198	0,174	0.192
	10,32	5.399	0,097	0.185
h	11.79	7,64	0,085	0 131
15th	12,06	15,80	0.083	0.063
20th	13,46	18,73	0.074	0.053
25th	15,04	25,44	0.067	0.039
30th	15,48	30,53	0,065	0,033

TABLE IV Dynamic Stress Output of Two Typical Prismatic Beam Elements of Turbogenerator Foundation Computer Models

Unit of force-KN, moment-KN metre, time-sec.

Element No.*	Stress Component		Maximum Value		Time at Maximum
43 Model A_2	Axial	Axial	95,43	95.43	2.12×10^{-2}
	Shear	Shear	12.66	12.66	2.62×10^{-2}
	Shear	Shear	2.602	2.602	6.37×10^{-2}
	Torsion	Torsion	0,546	0.546	$9,75\times10^{-2}$
	Moment	Moment	16.22	8.718	1.50×10^{-2}
	Moment	Moment	91.03	43.19	1.38×10^{-2}
10 Model B_2	Axial	Axial	75,64	75.64	$2,13\times10^{-2}$
	Shear	Shear	4,25	4.25	1.37×10^{-2}
	Shear	Shear	0.736	0.736	$1,50\times10^{-2}$
	Torsion	Torsion	0,140	0.140	4.00×10^{-2}
	Moment	Moment	5.57	9.53	$4,50\times10^{-2}$
	Moment	Moment	28.9	56.75	1.38×10^{-2}
41 Model A_2	Axial	Axial	30.94	30.94	9.40×10^{-2}
	Shear	Shear	6.22	6.22	9.50×10^{-2}
	Shear	Shear	152,6	152.6	1.25×10^{-2}
	Torsion	Torsion	0,836	0,836	6.12×10^{-2}
	Moment	Moment	251,1	483.1	1.25×10^{-2}
	Moment	Moment	21,7	11.78	9.62×10^{-2}
42 Model A_2	Axial	Axial	34,37	34.37	8.90×10^{-2}
	Shear	Shear	7,41	7.41	8.80×10^{-2}
	Shear	Shear	151.6	151,6	1.25×10^{-2}
	Torsion	Torsion	0,836	0,836	6.12×10^{-2}
	Moment	Moment	483,1	246.1	1.38×10^{-2}
	Moment	Moment	11,80	24.50	9.00×10^{-2}
23 Model B_2	Axial	Axial	4,90	4.90	7.25×10^{-2}
	Shear	Shear	3.43	3,43	7.25×10^{-2}
	Shear	Shear	132,7	132.7	1.38×10^{-2}
	Torsion	Torsion	0,223	0,223	$8,00\times10^{-2}$
	Moment	Moment	191.1	445,7	$1,38\times10^{-2}$
	Moment	Moment	9,56	7.10	7.25×10^{-2}
24 Model B_2	Axial	Axial	4.13	4,13	7.62×10^{-2}
	Shear	Shear	2,91	2,91	$9,12\times10^{-2}$
	Shear	Shear	132.0	131.9	1.38×10^{-2}
	Torsion	Torsion	0,223	0,223	$8,00\times10^{-2}$
	Moment	Moment	445.7	187,6	$1,38\times10^{-2}$
	Moment	Moment	7,10	8.00	7.38×10^{-2}

* It may be noted that the dynamic stress outputs of element numbers 43/10, 41/42 and 23/24 respectively are to be compared. Element numbers 41, 42 and 43 belong to fixed base model and their corresponding numbers in coupled soil-structure interaction model are 10, 23 and 24 respectively.

Note: Stress outputs for an element are furnished for end I and end J.

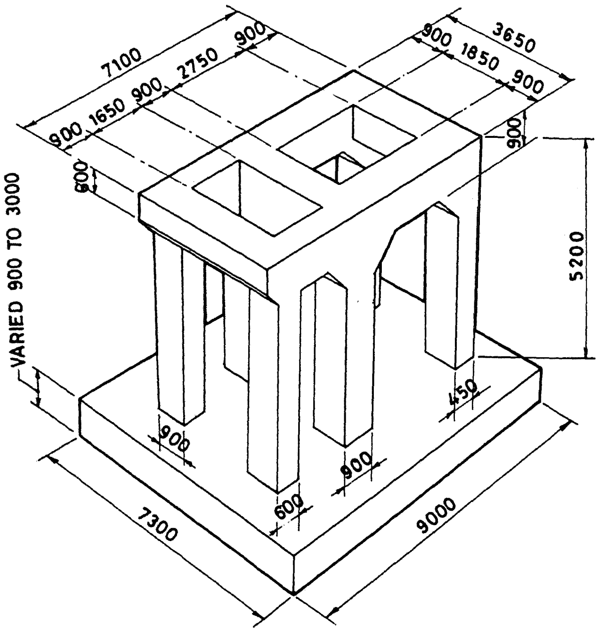


FIG. 1A

ISOMETRIC VIEW OF THE COMPRESSOR FOUNDATION.

SCALE - 1:150

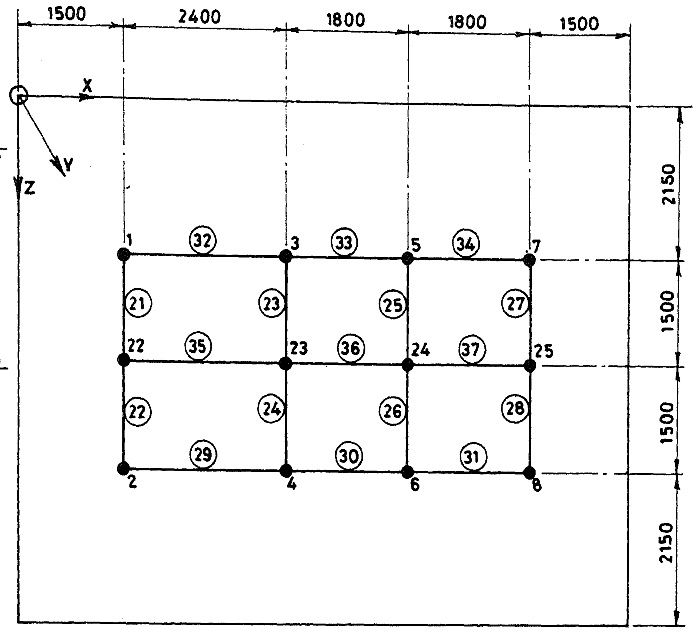
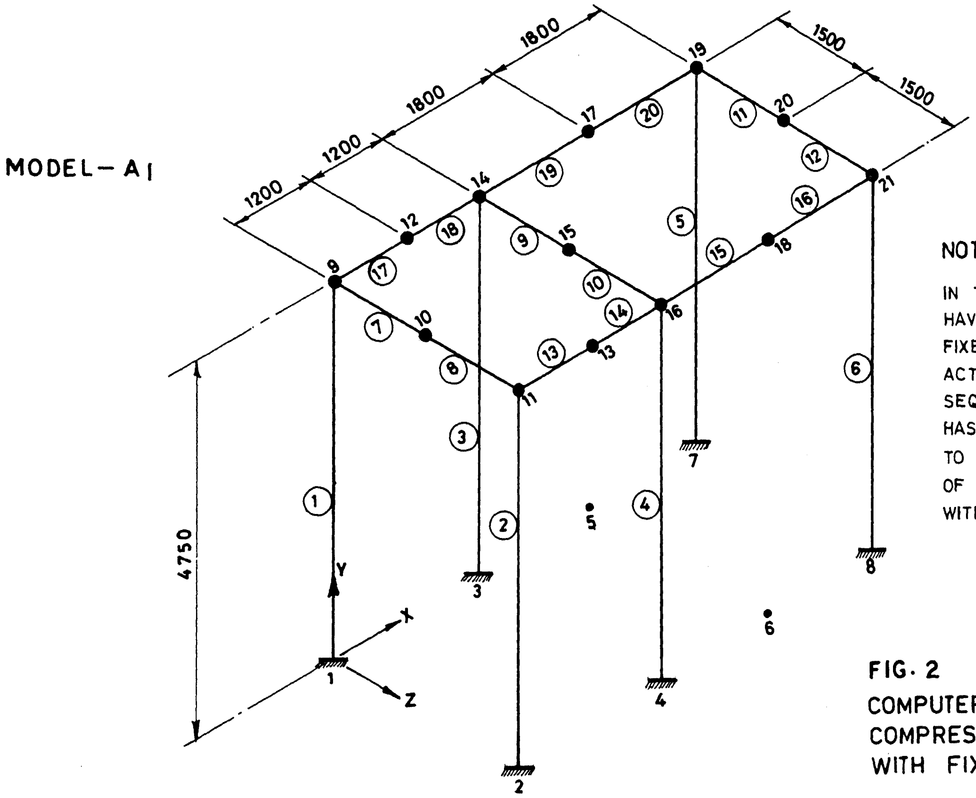


FIG. 1B

FINITE ELEMENT MODEL OF THE BOTTOM MAT.

SCALE-1:75



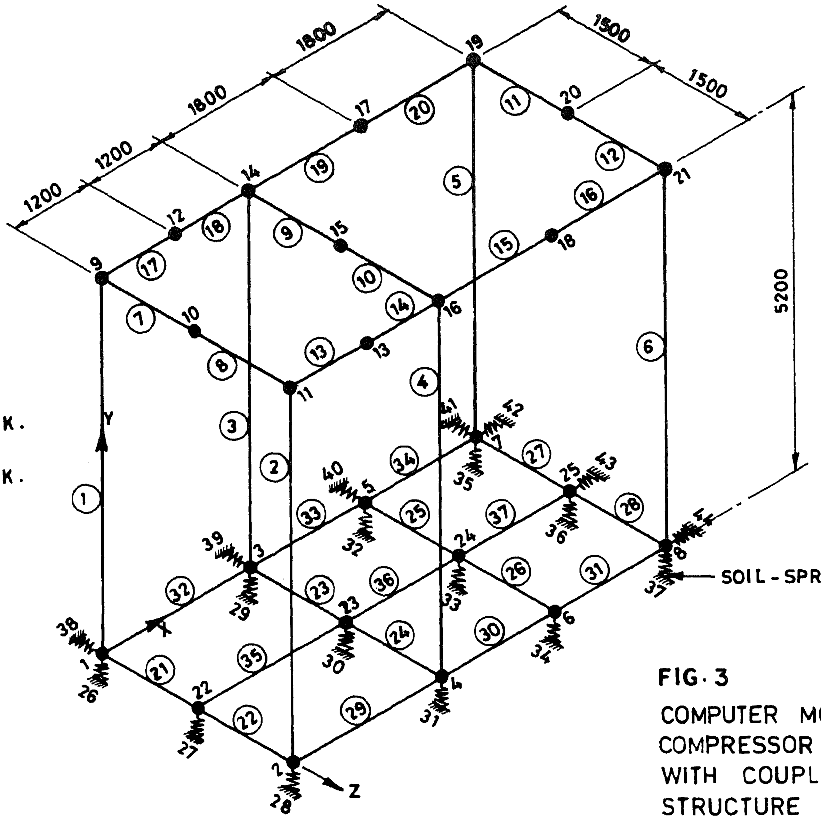
NOTE.

IN THIS MODEL NODES 1 TO 8 HAVE BEEN CONSIDERED AS FIXED (OR DELETED) i.e. NON-ACTIVE NODES. THE SAME SEQUENCE OF NODE NUMBERING HAS BEEN RETAINED IN ORDER. TO FACILITATE THE COMPARISION OF RESULTS OF ANALYSES WITH THE PREVIOUS MODEL.

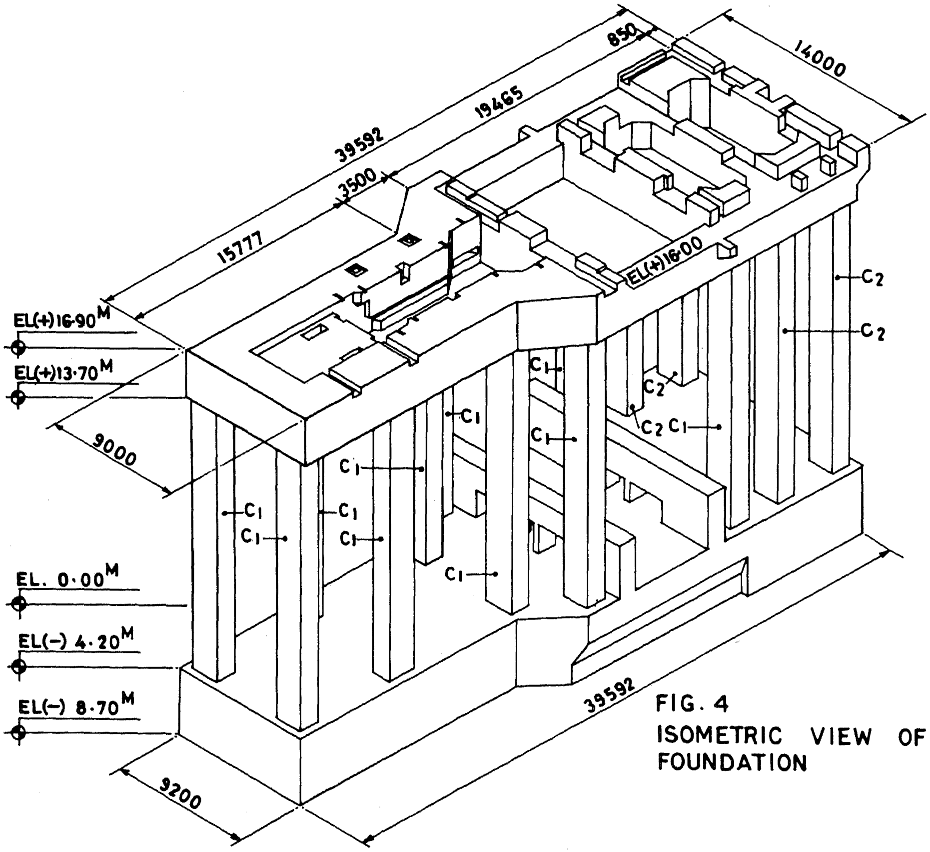
FIG. 2

COMPUTER MODEL FOR COMPRESSOR FOUNDATION WITH FIXED-BASE

MODEL- B₁
WITH RAFT 1·0 M THICK.
MODEL – C₁
WITH RAFT 3·0 M THICK.



FIG· 3
COMPUTER MODEL FOR COMPRESSOR FOUNDATION WITH COUPLED SOIL - STRUCTURE INTERACTION.



COLUMN	SIZE
C₁	1800 X 1300
C₂	1800 X 1200

FIG. 4
ISOMETRIC VIEW OF TURBO-GENERATOR FOUNDATION

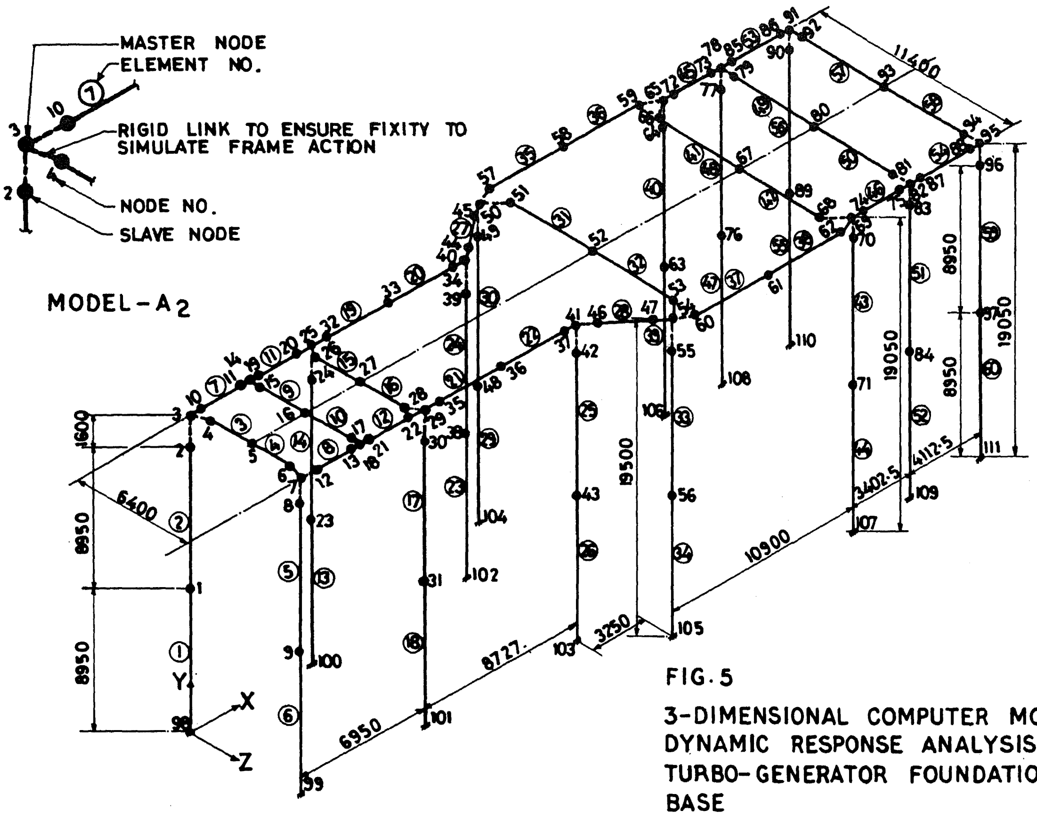


FIG. 5

3-DIMENSIONAL COMPUTER MODEL FOR DYNAMIC RESPONSE ANALYSIS OF 500 M.W. TURBO-GENERATOR FOUNDATION WITH FIXED BASE

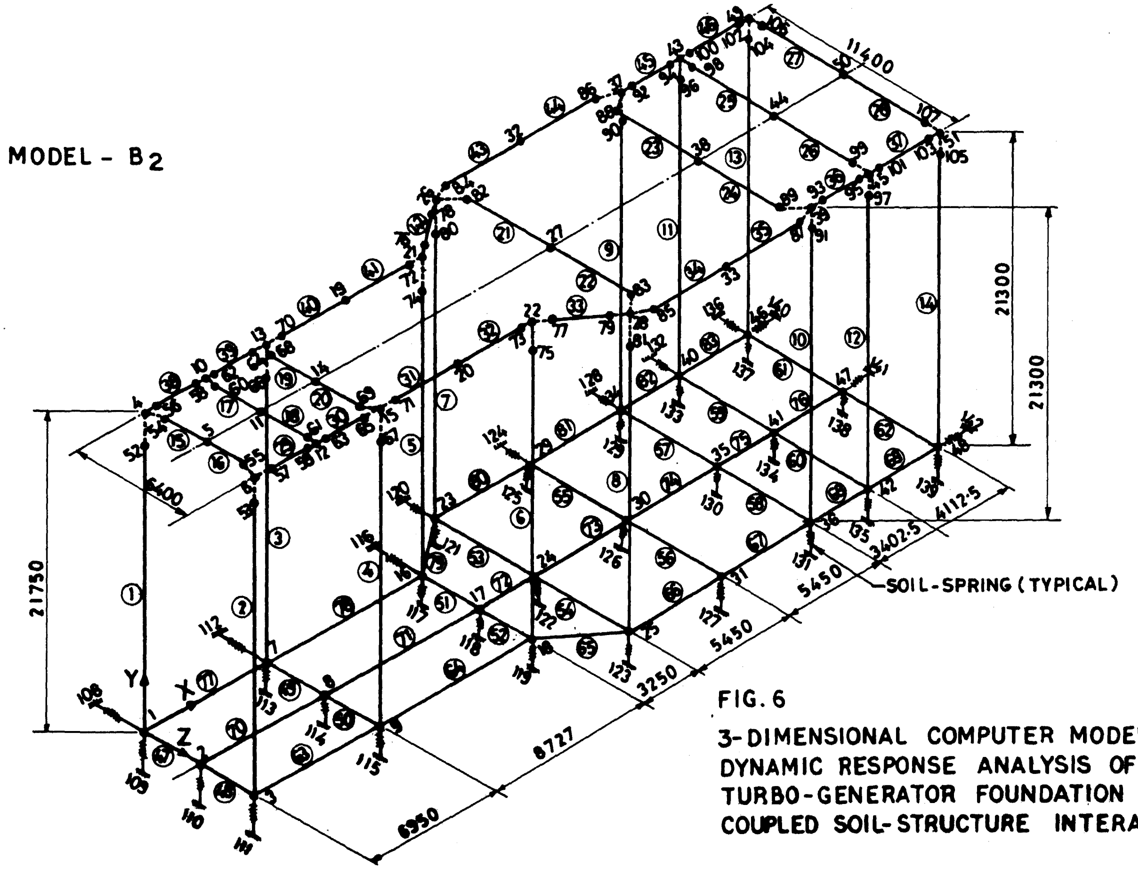


FIG. 6

3-DIMENSIONAL COMPUTER MODEL FOR DYNAMIC RESPONSE ANALYSIS OF 500 M.W. TURBO-GENERATOR FOUNDATION WITH COUPLED SOIL-STRUCTURE INTERACTION.

and other service loads must meet the machine manufacturers' stringent design stipulations to guard against shaft misalignment.

Once the trial design is judged satisfactory, the computer analysis for the proposed frame foundation may be performed. For the two case studies considered in this paper, the idealised analytical computer models viz. A1, B1, A2 and B2 are shown in Figs. 2, 3, 5 and 6 respectively.

Machine Data & Relevant Design Parameters

The basic machine data and related soil and other relevant parameters considered for the analysis of two foundations are as mentioned below :

Compressor Foundation

Total machine weight= 680 KN, Rotor weight= 20 KN, Machine speed = 7000 cpm (both turbine and compressor)
Dynamic modulus of elasticity of concrete $= 3.6 \times 10^7$ KN/sq.metre,
Static modulus of elasticity of concrete $= 2.85 \times 10^7$ KN/sq.metre,
Poissons ratio of concrete = 0.15
Average viscous damping = 5% of critical,
Density of concrete = 24 KN/cubic metre,
Shear modulus of soil = 6700 KN/sq.metre,
Poisson's ratio of soil = 0.45
Allowable bearing pressure of soil = 75 KN/sq.metre

Turbogenerator Foundation

Total machine weight = 23,638 KN
Rotor weight = 1919 KN
Machine speed = 3000 cpm
Shear modulus of soil = 117000 KN/sq.metre
Poisson's ratio of soil = 0.30
Allowable bearing pressure of soil = 300 KN/sq.metre
All data related to concrete material are similar as stated above.

In the typical forced response analysis results shown in Table IV, the maximum allowable unbalanced forces as furnished by the machine manufacturer are considered to be acting at bearing no.3 which corresponds to node 67 for model A2 and node 38 for model B2 respectively. These unbalanced forces are (1) vertical force, Fy, $= \pm$ 488 KN and (2) transverse force, Fz, $= \mp$ 166 KN acting with 90 degree phase difference to Fy.

Modeling of Idealised Systems

Isometric view of the computer models, which are predominantly composed of prismatic beam elements, for the compressor and turbogenerator foundations are shown on Figs. 2, 3, 5 and 6. In soil-structure interaction models, the beam elements at base level are connected to soil springs. The foundation mat may be represented by plate elements also. These models are suitable for use in any finite element structural analysis program with static and dynamic capabilities. Because of the complexity and expense of vigorously computing the effects of ratiation damping in the foundation an equivalent viscous damping for the soil-structure system is considered and this concept may be reliable since the top half of both the foundations are having uniform mass and stiffness distributions. The soil is modelled in both the cases by using springs at base level of space frame models to represent horizontal and vertical stiffness of the soil which also includes effect of footing embedment. These stiffnesses are derived from elastic half-space theory. These spring stiffnesses are dependent on the shear modulus which in turn varies with the level of shear strain in the soil. Hence for linear elastic models, spring stiffnesses should be incorporated corresponding to a value of shear strain which is less than the maximum expected shear strain.

Discussion on Results of Analysis

A close scrutiny of the results furnished through Tables I to IV reveal that mode shapes, predominant mode of a given structure, static and dynamic stress outputs are all affected if soil-structure interaction are included in the analysis. Since realistic values of soil stiffnesses depend fully on accurate field determination of low strain shear modulus of the supporting soil, which in the opinion of the authors is not yet an established and definitive procedure, the validity of carrying out such rigorous analysis may be questioned. Moreover, while fixing up other important parameters like dynamic elastic modulus of concrete, damping of concrete frame and supporting soil no uniform and rational basis is followed. But variations of these parameters will significantly affect the outcome of entire analysis eventhough model may remain same. Similarly the dynamic stress outputs and effective vibration amplitudes will be influenced considerably in the forced response analysis if the unbalanced forces data change arbitrarily. In view of these factors, starting from basic data processing to actual analysis and design; a unified approach should be adopted on an international basis.

CONCLUSIONS

The paper emphasizes the need for analysis and design of framed type turbo-machine and centrifugal compressor foundations with coupled soil-structure interaction due to its significant influence on dynamic response and static stress analysis. At the same time, a meaningful and unified approach in establishing and adopting realistic machine load data and relevant design parameters in order to make such rigorous analysis usable, is also highlighted.

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