SEISMIC REQUALIFICATION OF EXISTING CONCRETE STRUCTURE FOR NUCLEAR FUEL CYCLE FACILTIY

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ABSTRACT. Structures are designed to meet certain demands of strength, serviceability and stability. Equivalent static method and response spectrum method are popularly used as per Indian seismic standards for analysis and design of structures. However, during its service life, there may be revision of the functional requirements of the structure, the seismic ground motion parameters, or the codes, for which the structure would be required to be re-qualified. For this purpose, various aspects like actual loading, actual strength, higher damping and ductility might be useful for satisfying the seismic demand with the existing structure. In this paper, the strategy adopted for the requalification exercise would be explained step by step. This would be followed by the reanalysis and design check results from a case study wherein a RC structure of a nuclear fuel cycle facility would be re-qualified for higher ground motion, implementing the aforementioned advantages, as required.

Keywords: Seismic, Requalification, Concrete Structure.

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INTRODUCTION

Civil structures of nuclear safety related process plants designed and constructed during the last few decades were designed as per codes/ standards and guidelines prevailing at the time of their design, although older plant structures were robustly constructed. The worldwide concern and experience shows that assessment of seismic margin of an existing nuclear safety related process plant can become necessary due to followings:

1. Evidence of a greater seismic hazard at the plant site then expected at the time of its design and construction.
2. Lack of aseismic design at the time of its design and construction.
3. Change and modification in functional requirement, increment in dead and live loading due to revised functionality which was not considered at the time of its design and construction.
4. Consideration of changes in actual strength of structure or structural members found out from non destructive or partial destructive testing.
5. New technical findings like seismic vulnerability of some of the structure.
6. Revisions and up-gradation in the design codes/ standards and guidelines based on latest research.
7. Regulatory requirements as a part of periodic safety reviews.

Above mentioned concerns draw the attention of plant authority, designers and researcher towards the need of seismic evaluation which is intended to be applied after plant has been constructed. Such post construction evaluation programmes evaluate the current capabilities of the nuclear safety related civil structure of plant to withstand the seismic concern i.e. review basis ground motion (RBGM) along with other operating loads.

In present paper, focus is mainly given on the two stages of seismic evaluation strategy. In first stage, the existing structure is first analyzed and design is checked for design strength and design loads considered at the time of design of structure in combination with revised seismic review basis ground motion of assessed seismic hazard as an external event. The deficient structure or part of structure is further analyzed and designed for design strength and actual loads calculated by revising loads present on each part of plant in combination to RBGM in second stage of evaluation programme. The seismic evaluation is performed considering static and dynamic analysis with effect of soil structure interaction effect as per ASCE4-98 [1]. The design checks are performed according to the prevailing codes and standards [2, 3, 4].Enhanced structural damping and ductility have been considered according to the international guidelines of seismic evaluation of existing plants [5,6,7] for both the stages of evaluation programme and results are presented subsequent sections.

DESCRIPTION OF EXISTING STRCTURE

The structures under consideration have an area of 52m x 37.5m having Reinforced Cement Concrete (RCC) thick shell shear walls. Various process and maintenance areas are located centrally in an area of 20m x 48m on a continuous raft of 1.5m thick. The raft is resting on firm soil at 4.0m below finish floor level. Some of the RC thick shell shear walls extend upto13.5m above raft level, whereas, the few extends upto 11m above raft level.

Above the cell top, cell operating floor is located at 12.5m level which is essentially a crane hall of 14m x 48m x 11.0m height with 20T EOT crane facility. On the southern side of the cells 7.5m wide bay to the full length of the cells with an intermediate floor slab at 4.75m level and roof slab at 11.3m level provides access to the cells and basement in addition to housing inactive maintenance and other utility rooms. On the northern side of the cells a 10.5m wide bay to the full length of the cells with an intermediate floor at 4.75m level and roof at 10.5m level provides various lab facilities and houses cell operating areas. On the eastern side of the cells a 4.0m wide bay along the cell wall with intermediate floor at 4.75m level and roof at 10.5m level serves as corridor for movement of men and material from one side to the other. A 4.0m wide area at 10.5m roof level adjacent to the cells on eastern side.

MATERIALS PROPERTIES

The following table 1 gives material properties considered in the study for concrete and reinforcement of the existing structure.

Table 1 Material Properties

CONCRETE		REINFORCEMENT BAR	
Grade of Concrete	:M25	Grade of Steel	: Fe415
Unit Weight of Concrete	: 25 KN/m^3	Yield Strength	: 415 N/mm^2
Modulus of Elasticity	: 25 x 10^3MPa	Modulus of Elasticity	: 2 x 10^5MPa
Poisson’s ratio	: 0.2	Poisson’s ratio	: 0.3
Coefficient of thermal Expansion	: 9.5×10^{-6} $/^0C$	Coefficient of thermal Expansion	: $12 \times 10^{-6}/^0C$

GEOTECHNICAL PROPERTIES

All soil properties like shear modulus, density and poison’s ratio of soil for the re-evaluation are based on the existing design basis which was considered at the time of analysis of original design strength and design loads of existing structure. Accordingly, the safe bearing capacity at 4.0m below ground level is 40T/m^2. The re-evaluation of existing structure will be carried out using a safe bearing capacity of 40T/m^2, 4m below ground level. The shear wave velocities of the site soil $(\upsilon s = \sqrt{G/\rho})$ are also calculated for best estimate (1G), lower estimate (0.5G) and higher estimate (2G) of shear modulus (G) to consider uncertainty in the soil and further used for soil structure interaction analysis by impedance function approach as given in the reference [1]. The details of geotechnical parameters are presented in Table 2.

Table 2 Geotechnical Properties

SR NO.	PROPERTIES		VALUES
		Lower limit	6.75
1	Shear Modulus (GPa)	Best estimate	13.75
		Higher limit	27.45
		Lower limit	1630
2	Shear wave velocity (m/Sec.)	Best estimate	2327
		Higher limit	3287
3	Density (T/m^3)		2.54
4	Poisson’s ratio		0.32
5	Design Safe bearing capacity of soil (T/m^2) at 4m.		40

LOADING DETAILS

The brief descriptions of the basic load cases considered for design re-evaluation of existing RC civil structure are listed below:

Dead Loads (DL)

The weights of all permanent construction, including walls, floors, roofs, partitions and stairways will be considered as dead load. All interior and exterior brick walls are considered 115mm and 230mm thickness respectively. The unit weight of materials for computing self-weight will be according to Indian standard [8].

Live Loads (LL)

Live loads will be considered based on the loading data obtained in the design basis. These live loads were considered at the time of analysis of original design strength and design loads of existing structure i.e. Stage I of seismic evaluation strategy. However, for Stage II of the seismic evaluation strategy, live load is calculated by visiting every part of the plant structure and actual loads present on the structure (i.e. the plant 'as is') Live load on the accessible and inaccessible roofs are considered as 150 and 75 kg/m^2 respectively [8].

Crane Loads (LL)

The loading of 20T capacity EOT Crane is considered in the analysis. For static analysis both empty weight and lifted capacity will be considered whereas in seismic analysis only empty weight of crane will be considered. The impact factors would be considered for static analysis according to the latest Indian standard [8].

Earthquake Load (EL)

Horizontal spectral acceleration for RBGM is considered according to the site-specific spectra available for the plant site under consideration having 0.2g peak ground acceleration (Figure 1). Vertical component of the seismic spectra will be considered as 2/3 of horizontal spectra.

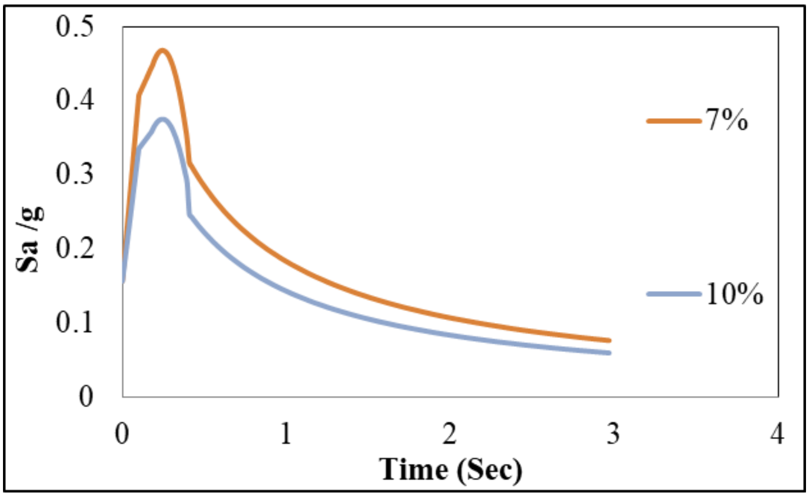


Figure 1 Site specific spectra for RBGM

Load Combinations

The primary load cases are combined in the limit state design check as follows [8].

i. 1.4 DL + 1.6 LL
ii. DL + LL ±EL
Where, DL = Dead load, LL = Live load, EL = Seismic loading due to RBGM earthquake.

MODELLING AND ANALYSIS METHODOLOGY

Modelling and analysis methodology for re-evaluation have been outlined below for the existing nuclear safety related RC structure. The commercially available 3D structural analysis software is used for the analysis [9]. The super structure will be modelled using 3D frame elements. The RCC walls will be modelled using shell elements. The effect of slab will be considered using rigid diaphragm action. The beam-column joints will be considered as rigid. Figure 2 shows isometric view of 3D finite element model of structure.

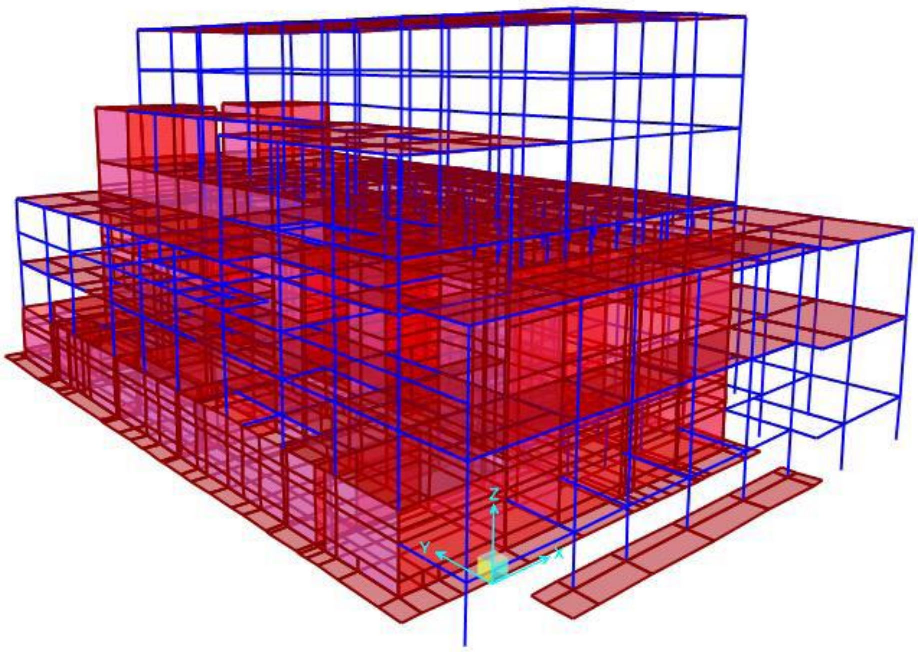


Figure 2 Isometric view of Structure

Soil structure interaction (SSI)

Soil structure interaction (SSI) will be considered according to Table 3.3-3 of ASCE 4-98 [1] to assess its influence on structural responses. In case of isolated rectangular footings, SSI will be considered using six degrees of freedom (DOF) spring and three DOF dashpot systems. In case of Raft/Mat foundation, only translational springs and dashpots will be modelled and the SSI will be considered using distributed area springs and dashpot system. The uncertainties in the soil properties will be considered in the analysis for a given range of soil properties as in Table 1. The embedment effects will be neglected in calculation of foundation impedance, as the embedment length of the cells in building is significantly less than 30% of the equivalent radius [1].

Structural Analysis

Seismic analysis will be carried out on simplified mathematical model using response spectrum method. The individual mass of equipment/piping is very low compared to the structural mass, structure equipment/piping interaction will not be considered in the analysis. However, the mass of all the equipment's /piping will be considered in the analysis. The seismic weight computation for modal analysis is carried out from full dead load, half of the varying component of the live load. The damping ratio of 10% is considered as per Table III.1, Appendix III [5]. The equivalent modal damping values for structural system with SSI are evaluated using strain energy equivalence. The inelastic energy absorption factor (Fμ) is used to modify the seismic demand (to account for the ductility in the structural elements) according to Clause 7.3.1 [5]. Accordingly, Fμ values for RCC columns and shear walls are considered as 1.5. In case of beams Fμ is taken as 1.75 and 1.25 in flexure and shear respectively. The modal combination rules will be according to clause 2.3.5, and the direction combination will be as per the clause 2.3.6 [10].

STRUCTURAL ANALYSIS RESULTS

The summary of the base reactions obtained in the basic load cases and reactions under various load combinations considered for design are presented in Table 3

Table 3 Summary of reactions at the base of the structure

OUTPUT CASE	CASE TYPE	GLOBAL FX (TON)		GLOBAL FY (TON)		GLOBAL FZ (TON)	
		STAGE I	STAGE II	STAGE I	STAGE II	STAGE I	STAGE II
Dead	Static	0.0	0.0	0.0	0.0	19714.3	19714.3
Dead_slab	Static	0.0	0.0	0.0	0.0	1897.6	1897.6
Dead_wall	Static	0.0	0.0	0.0	0.0	1597.7	1597.7
Dead_crane	Static	0.0	0.0	0.0	0.0	27.0	27.0
Live	Static	0.0	0.0	0.0	0.0	8890.4	7890.4
Live_roof	Static	0.0	0.0	0.0	0.0	172.0	172.0
Live_crane	Static	0.0	0.0	0.0	0.0	61.0	61.0
Stair case	Static	0.0	0.0	0.0	0.0	26.7	26.7
Floor_finish	Static	0.0	0.0	0.0	0.0	317.7	317.7
EQ-X	RespSpec	5353.7	4830.6	390.1	410.7	198.5	185.1
EQ-Y	RespSpec	393.5	413.9	5536.5	4959.8	201.1	219.6
EQ-Z	RespSpec	122.6	114.1	127.9	140.3	2778.3	2618.2
DL+LL	Combination	1284.4	1284.4	-718.9	-718.9	34199.4	29754.2
1.4DL+1.6LL	Combination	1798.2	1798.2	-1006.4	-1006.4	49703.8	42591.5
DL+LL+EQ	Combination	6654.0	6134.0	4832.8	4259.9	36992.0	32388.1
DL+LL+EQ	Combination	-4085.1	-3565.2	-6270.6	-5697.6	31406.7	27120.3

SEISMIC ANALYSIS RESULTS

The fivepredominant natural periods (in the order of their mass participation) based on best estimated soil spring properties are compared with corresponding lower and upper limit values in Table 4 to 6. The equivalent damping ratios in each mode after soil structure interaction are also shown in the same table. A total of 500 modes are considered in the response spectrum analysis. Further from Table 7, the sensitivity of SSI on base reactions is assessed. The lateral defection at different floor level is tabulated in Table 8.

Table 4 Comparison of Predominant Natural Periods of the Structure with different foundation soil properties in X-direction.

SR. NO	LOWER LIMIT						BEST ESTIMATE						UPPER LIMIT					
	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D
1	0.1084	0.1075	0.2669	0.2911	0.1488	0.1495	0.0999	0.0963	0.3003	0.3424	0.1269	0.1299	0.0952	0.0936	0.1407	0.1803	0.1057	0.1078
2	0.1094	0.1038	0.1764	0.2149	0.1328	0.1460	0.0985	0.0925	0.1675	0.0496	0.1148	0.1219	0.0956	0.0820	0.1337	0.1112	0.1059	0.1162
3	0.1165	0.0411	0.0595	0.0454	0.1088	0.1576	0.0792	0.0855	0.0384	0.0442	0.1137	0.1378	0.0904	0.0884	0.1292	0.1026	0.1165	0.1117
4	0.1108	0.1091	0.0386	0.0323	0.1102	0.1059	0.0880	0.0970	0.0259	0.0331	0.1220	0.1045	0.0839	0.0880	0.0779	0.0786	0.1169	0.1085
5	0.0816	0.0802	0.0281	0.0289	0.1207	0.1196	0.3074	0.0925	0.0233	0.0279	0.1003	0.1135	0.0752	0.0743	0.0396	0.0394	0.1053	0.1054

Table 5 Comparison of Predominant Natural Periods of the Structure with different foundation soil properties in Y-direction.

SR. NO	LOWER LIMIT						BEST ESTIMATE						UPPER LIMIT					
	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D
1	0.1010	0.0983	0.3730	0.3571	0.1642	0.1613	0.0952	0.0855	0.2354	0.2342	0.1267	0.1378	0.0904	0.0884	0.2577	0.1470	0.1165	0.1117
2	0.0944	0.0918	0.1364	0.1448	0.1510	0.1484	0.0880	0.0925	0.1553	0.1664	0.1220	0.1219	0.0839	0.0820	0.1601	0.1229	0.1169	0.1162
3	0.1138	0.0916	0.0535	0.0464	0.1036	0.1138	0.0877	0.0925	0.0610	0.1039	0.1137	0.1135	0.0780	0.0880	0.0500	0.1108	0.1030	0.1085
4	0.0966	0.1136	0.0268	0.0406	0.1087	0.1025	0.0924	0.0782	0.0512	0.0476	0.1048	0.1088	0.0932	0.0770	0.0380	0.0819	0.1030	0.1037
5	0.3079	0.3079	0.0254	0.0268	0.1008	0.1007	0.0792	0.0770	0.0328	0.0297	0.1137	0.1073	0.3071	0.0774	0.0226	0.0421	0.1001	0.1018

Table 6 Comparison of Predominant Natural Periods of the Structure with different foundation soil properties in Z-direction

SR. NO	LOWER LIMIT						BEST ESTIMATE						UPPER LIMIT					
	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D	SI-P	SII-P	SI-M	SII-M	SI-D	SII-D
1	0.0520	0.0498	0.1045	0.2094	0.1540	0.1842	0.0456	0.0435	0.2823	0.1273	0.1821	0.1517	0.0395	0.0394	0.0792	0.0938	0.1216	0.1266
2	0.0512	0.0505	0.1018	0.0916	0.1805	0.1705	0.0438	0.0434	0.1011	0.1039	0.1423	0.1352	0.0429	0.0422	0.0738	0.0691	0.1124	0.1103
3	0.0532	0.0491	0.0813	0.0566	0.1481	0.1371	0.0426	0.0447	0.0368	0.0712	0.1224	0.1279	0.0419	0.0355	0.0433	0.0425	0.1129	0.1137
4	0.0518	0.0515	0.0625	0.0348	0.1437	0.1178	0.0462	0.0434	0.0338	0.0558	0.1113	0.1232	0.0445	0.0367	0.0417	0.0384	0.1088	0.1094
5	0.0532	0.0492	0.0480	0.0329	0.1323	0.1190	0.0411	0.0409	0.0175	0.0310	0.1185	0.1237	0.0421	0.0412	0.0306	0.0365	0.1059	0.1074

Nomenclature:
Stage I – Period (Sec.):- SI-P
Stage II – Period (Sec.):-SII-P
Stage I – Mass Participation ratio: l-SI-M
Stage II – Mass Participation ratio:- SII-M
Stage I – Effective Damping (%):– SI-D
Stage II – Effective Damping (%):- SII-D

Table 7 Comparison of Base reaction considering soil structure interaction

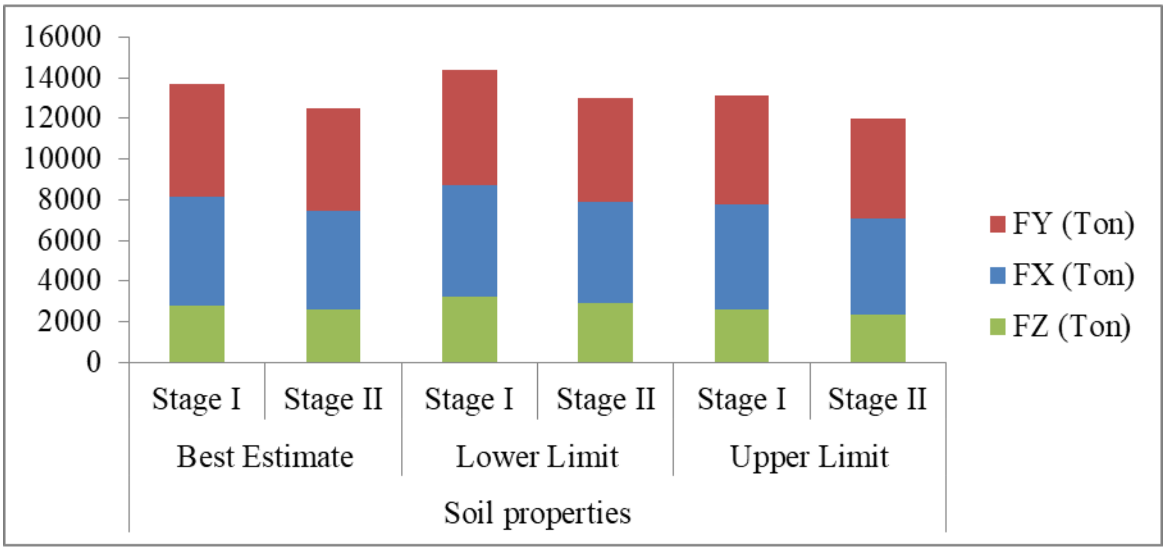
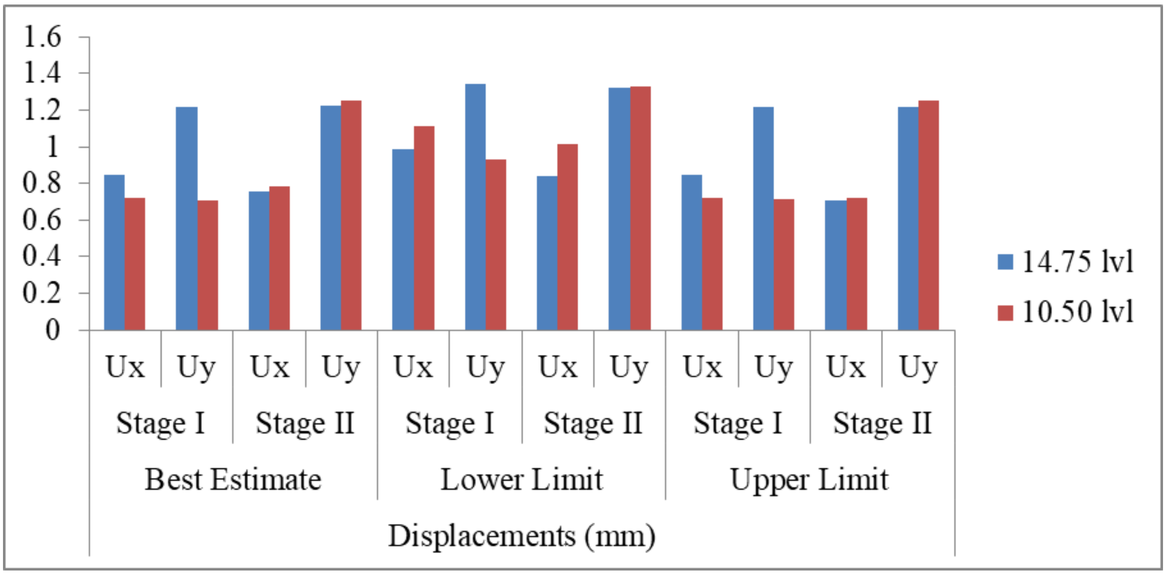


Table 8 Displacement at different floor levels (DL+LL±EQ)



DESIGN CHECK

Static Load Case

The design margins available under static loading in all beams using Limit State Method (LSM) are calculated. It can be seen that maximum Utility Check (UC) ratio (UC ratio is defined as the ratio of stress resultants in the member under any load case, to the respective capacity of the section) in all beams is 0.88 and 0.86 in bending and shear in limit state design.

The design margins available under static loading in all columns using LSM are also calculated. Columns subjected to combined flexure and bending need to be checked by using LSM [3]. It can be seen that the maximum UC ratio in all columns is 0.692.The isolated and strip foundation has been checked against allowable bearing pressure, uplift and reinforcement for static load case and no failures has been observed. The evaluation of RC cell walls are done by comparing with the required reinforcement obtained in structural analysis programme with actual reinforcement provided. It was found that reinforced concrete (RC) wall is safe in the static load case.

Seismic Load Cases

The design margins available under seismic loading in all beams using LSM are calculated on the envelop of the results of "Best Limit", "Upper Limit" and "Lower Limit" soil properties. It can be seen that the maximum UC ratio in all beams is 0.94 (bending), 0.86 (shear) in limit state design. In Table 9 all failed beam sections along with the UC Ratios are summarized.
The design margins available under seismic loading in all columns using LSM are calculated. Columns subjected to combined flexure and bending need to be checked by using LSM [3]. It can be seen that the maximum UC ratio in all columns is 0.67.
The evaluation of RC cell walls is done by comparing with the required reinforcement obtained in structural analysis programme with actual reinforcement provided. It was found that RC wall is safe in the seismic load case.

Table 9 Beam failure summary in limit state design

FRAME ID	SECTION ID	LOCATION	LOAD CASE	UC RATIO IN STAGE I		UC RATIO IN STAGE II	
347	RB44 250x500	4.45	DL+LL±EQ	1.19	0.63	0.56	0.54
350	RB44 250x500	0.2	DL+LL±EQ	1.29	0.31	0.56	0.39
374	RB47 250x500	3.3	DL+LL±EQ	1.08	0.57	0.51	0.5
376	RB47 250x500	0.2	DL+LL±EQ	1.06	0.42	0.5	0.51

The isolated and strip foundation has been checked against allowable bearing pressure, uplift and reinforcement for seismic load case. It was found that the bearing pressure is below the foundation is less than the allowable bearing pressure in the case of all isolated and strip foundation under the seismic load case. Also, the reinforcement provided for the isolated and strip foundations are found to be adequate in seismic load case.
The overall summary of the design check of structural elements of existing RC civil structure of nuclear safety related process plant is shown in Table 10.

Table 10 Overall summary of the design check of structural elements of existing structure

STRUCTURAL ELEMENTS	STAGE I	STAGE II
Beam	LSM (Static) - No failure LSM (Seismic) - 4 beams failed	LSM (Static) - No failure LSM (Seismic) - No failure
Column	No failure	No failure
RC Cell Wall	No failure	No failure
Foundation Bearing pressure	No failure	No failure

Foundation Reinforcement	No failure	No failure
Foundation Uplift	No failure	No failure

SUMMARY AND CONCLUSION

The existing RC civil structure of nuclear safety related process plant is assessed for capacity of structure under seismic evaluation programme. In first stage, the existing structure analysed and designed for design strength and design loads considered at the time of design of structure in combination with revised seismic review basis ground motion of assessed seismic hazard as an external event. The deficient structure or part of structure is further analyzed and designed for design strength and actual loads calculated by revising loads present on each part of plant in combination with RBGM in second stage of evaluation programme.

In stage I, it was found that the four beams would failed under LSM for design strength and design loads in combination with revised seismic review basis ground motion. Whereas in stage II, all beams under limit state design checked and found have sufficient margins available against actual static and seismic loading. It was found that in both stage I and stage II, the RC walls and columns are having sufficient margin against design static and seismic loading. The bearing pressure is below the allowable bearing pressure for isolated footing and raft/strip footing in the static and seismic loading case. The reinforcement provided for the isolated and raft/strip foundations are found to be adequate for static and seismic load case.

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