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The Impact of Seismic Isolation and Soil Structure Interaction on the Power Plants Structures

Rania M.Elsepai.

Ph.D. Student, Faculty of Engineering, Cairo University, Giza, Egypt.

rania.elsepai.j@eng-st.cu.edu.eg

Hany A. Abdalla

Professor of Concrete Structures, Faculty of Engineering, Cairo University, Giza, Egypt.

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Abstract:

The case study in this research is particularly regarding the main and secondary containments in the safest type of the power plants which is the pressurized water reactor. The European pressurized reactor (EPR) is taken as a case of analysis. The reactor building containments are designed to withstandseismic events. The 3D modeling analysis which has been established by ABAQUS 2023 software for the containment structure would reveal the behavior and distribution of stress under the earthquake load combination case. The variation of soil types (clay, dense Sand&Gravel and rock) are considered as parameters of analysis and the foundation is studied for the fixed and isolated base with prestressing hoop and vertical prestressing configuration in the main containment wall as is common in the Russian reactor. The behavior of the main containment (prestressing wall) of the internal shield response behavior is studied due to exposure to Elcentro - Seismic excitation in case of fixed and isolated base.The base isolated system is more efficient for shielding and safety purposes than fixed base in all cases of soil types. Isolated basewould be preferred for using more than fixed base in vital structures such as power plant stations.

Keywords: Buttresses,Isolation, Power plants, Reactor, Seismic,Shielding, Vessel.

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1. INTRODUCTION

As shown in Fig. (1) power reactor is used in the power plants for electricity generation, propulsion of ships, district heating. Some reactors are used to produce isotopes for medical and industrial use and some run only for research. The reactor is known as an atomic pile, this device is used for initiation and controlling a self-sustained chain reaction. In the power plants 1 kg of Uranium -235 produces (7.2 x 10^{13}joules) whereas

1kg coal produces ($2.4x10^7$joules). Few years ago, due to the change of earth topography and tectonic instability, catastrophic and destroyed earthquake hit Turkey and Syria, in addition it is expected by the expertise to have frequent earthquakes in many other locations. Accordingly, warning and concern should be taken into consideration by structural engineers.

Typically, the usual anti-seismic design is based on the structural ductility that is the ability to undertake extensive plastic deformations which dissipate energy by hysteresis. In this kind of design large structural damages are allowed. Consequently, even if the structure collapse is prevented, expensive repairs are necessary after major earthquakes. In addition, in regular buildings the concept of seismic design is limited and focus on how to design safe building in lateral resistance represented by many members such as shear walls, braced frames and moment resistant frames. However, no protection is guaranteed to the instruments inside the vital structures such as power plant structures. Power plants are unique concrete structures which require a special type of concrete with special measures according to their function and performance to resist and deal with the effect of the surrounded environmental stressor (e.g. earthquake, flood, tornado, external hazards, missiles and aircraft hazard) without loss of their capability to perform their function safely. In addition, the operation process (e.g. high pressure, high temperature, emission of radiation, internal leakage) affect the power plants behavior. According to the American Concrete Institute [1], these types of structures which their minimum cross – sectional dimension of a solid concrete member exceed 900 mm are counted as massive structures. Thus, high density concrete is more efficient in this case,to achieve the structural safety. The new concept of seismic isolation knocked the door of modern seismic innovations technologies for vital buildings protections and integrity. Seismic isolators work by decoupling the building or structure from ground motion, allowing it to move more flexibly and absorb seismic energy [2]. Seismic isolator typologies areshown in Figs. (2).

Fig. 1.a A sample of the power plants Structure [3]

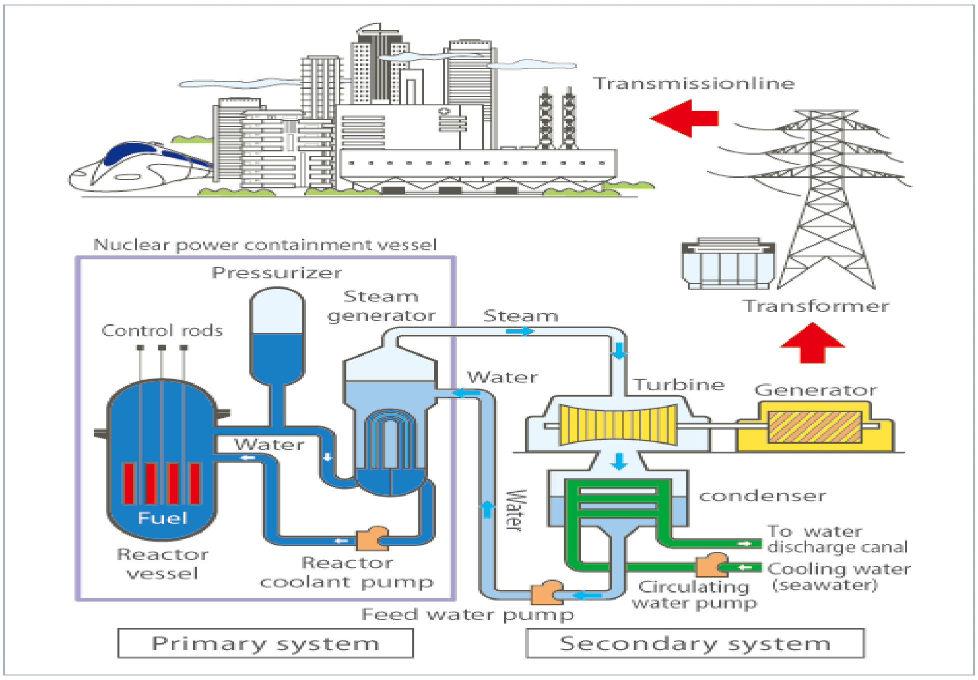


Fig. 1.b. Layout of Pressurized Water Reactor [4]

The acceleration of earthquake in particular location is function in the natural time period and the stiffness and mass of structure. On the other hand, as shown in Figs. (3), design spectra diagram has three stages according to the acceleration of earthquake value which is increasing with increasing of the natural time period of the structure then constant value in the second stage with increasing of the natural time period value, finally decreasing in the third stage with increasing of the natural time period value. In addition, the vast majority of buildings has approximate values of the natural time period as the following, 0.2 in rigid buildings and from 1 to 1.2 in flexible buildings. It means that the time period of any structure ranges between 0.2 to 1.0 second which is located in the third stage. Accordingly, to reduce the earthquake force which is called base shear force, the earthquake acceleration should be decreased by changing the stiffness. Flexible structures are considering in design by increasing its time period when the structure is subjected to earthquake or dynamic excitation, dynamic soil structure interaction occurs. The structure response depends on the interaction between three systems, structure, foundation, and the underlying soil. The analysis of soil structure interaction is the method of the collective response evaluation of the mentioned three linked system for specific ground motion. Accordingly, it should be taken into consideration. Eventually, the reactor building containments are supposed to be designed to withstand the internal accidents in case of exposing to external hazards such as seismic event[2].

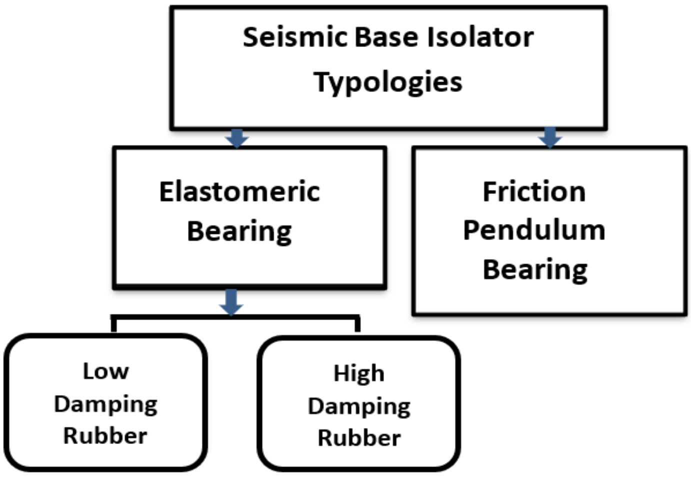


Fig.2.a Seismic Isolator Typologies [6]

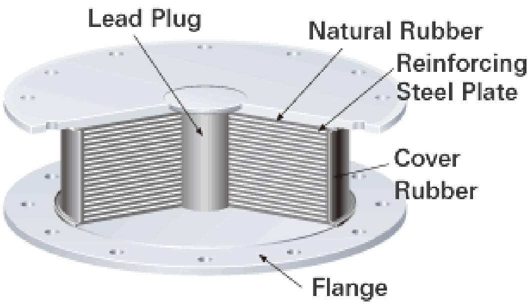


Fig. 2.b Lead Rubber Bearing (LRB) [6]

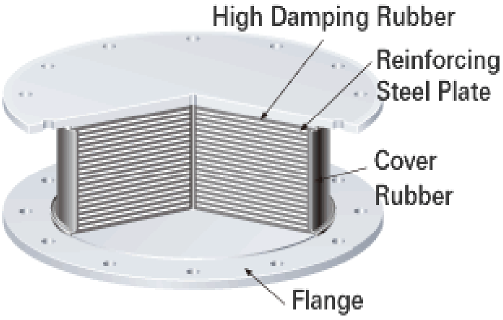


Fig. 2.c High Damping Rubber Bearing [6]

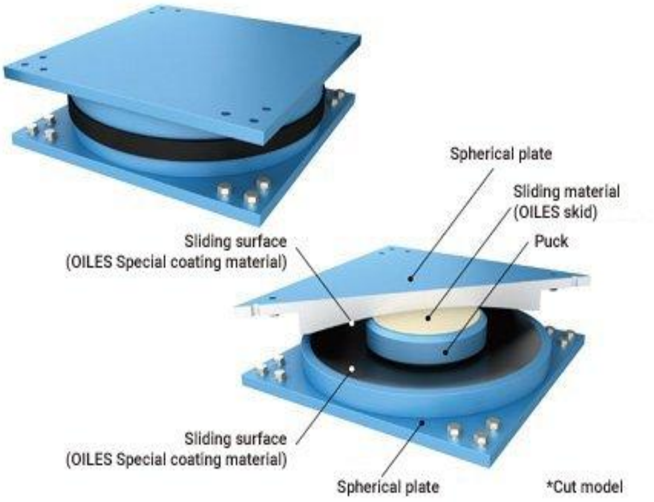


Fig. 2.d Friction Pendulum Bearing [7]

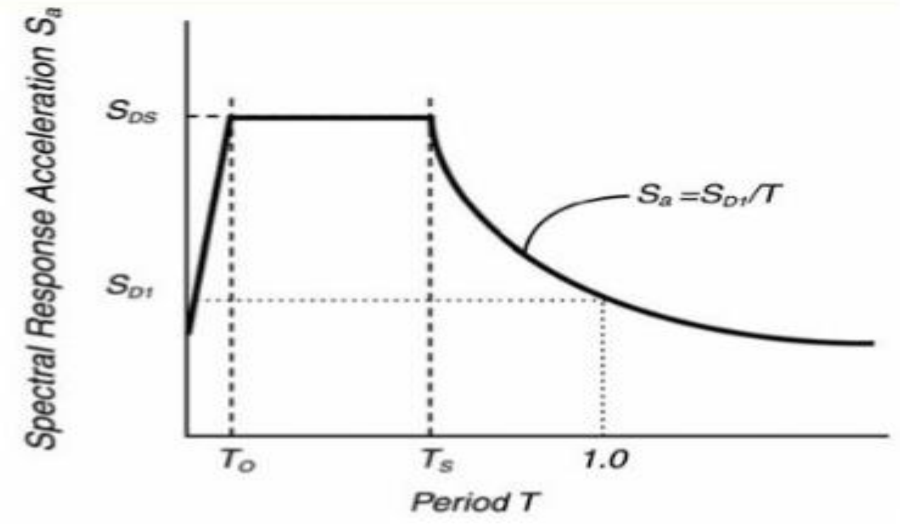


Fig. 3.a Design Response Spectrum [5].

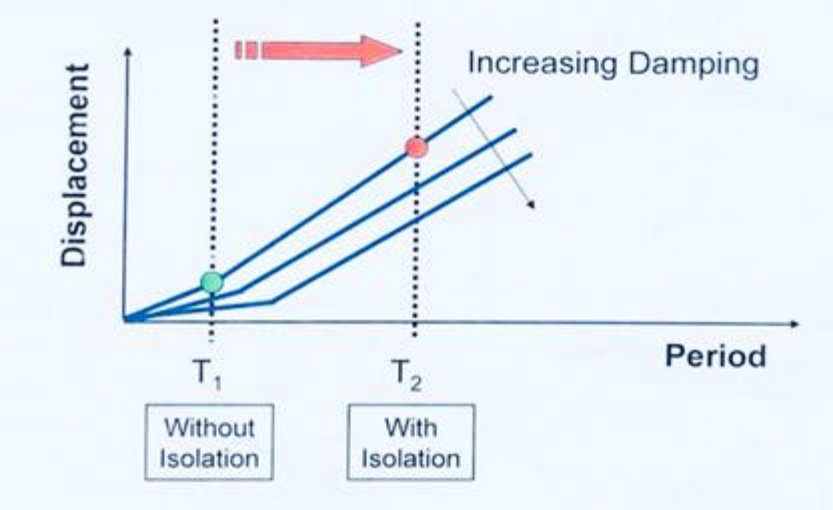


Fig. 3.b Seismic Isolation effect on Displacement Response Spectrum[5].

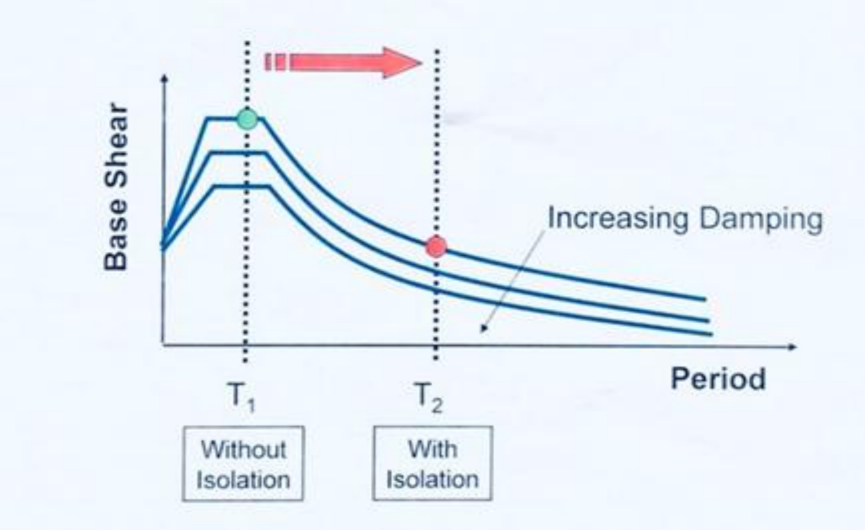


Fig. 3.c Seismic Isolation effect on Acceleration Response Spectrum [5].

2. METHODOLGY

The case study in this research is particularly regarding the main containment shown in Figs. (4), and (5). The European pressurized water reactors (EPR) was taken as a case of study. A 3D-finite element analysis is carried out for the main and secondary containments of the reactor building by using ABAQUS-2023 structural analysis program to study the affection of Seismic load on the pre-stressing containment which is called main containment, according to changing of some parameters such as underlyingsoil types (clay, rock, and dense sand-Gravel), with properties as shown in Table. (1). The second parameter is the typeof Foundation (fixedor isolated). The isolator properties are shown in Fig. (8) and Magnetite heavy weight concrete was used, with the properties shown in Table. (2). The main containment behavior responseisstudied according to the mentioned parameters.

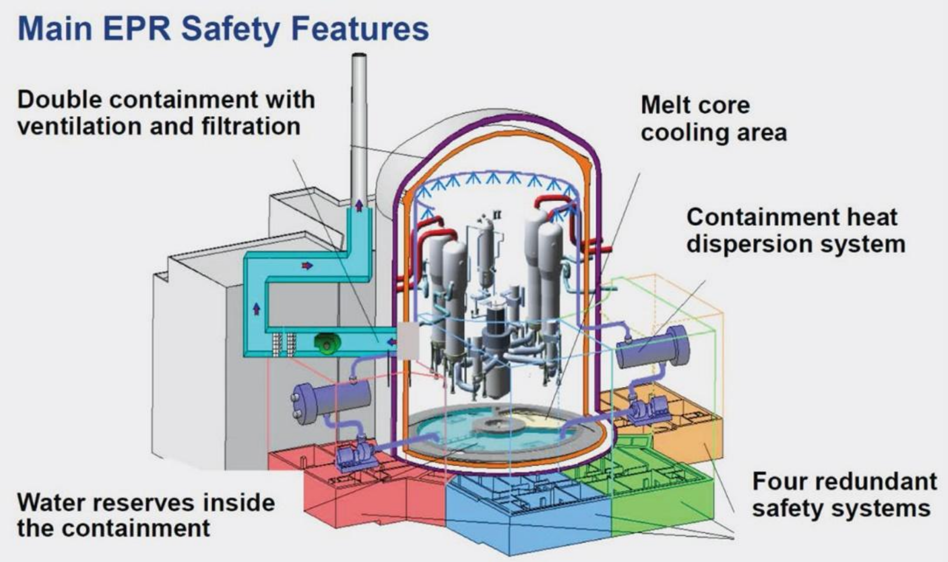


Fig. 4.a European Pressurized Water Reactor with Fixed Base [3].

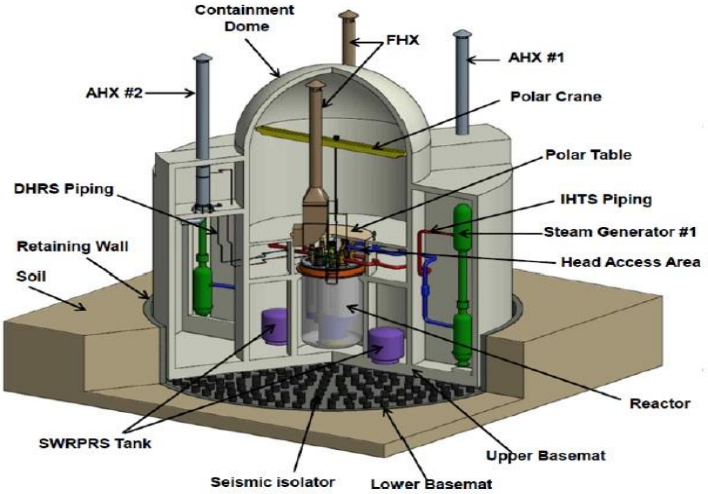


Fig. 4.b Arrangement of the Containment in the Reactor Building with Base Isolation [13].

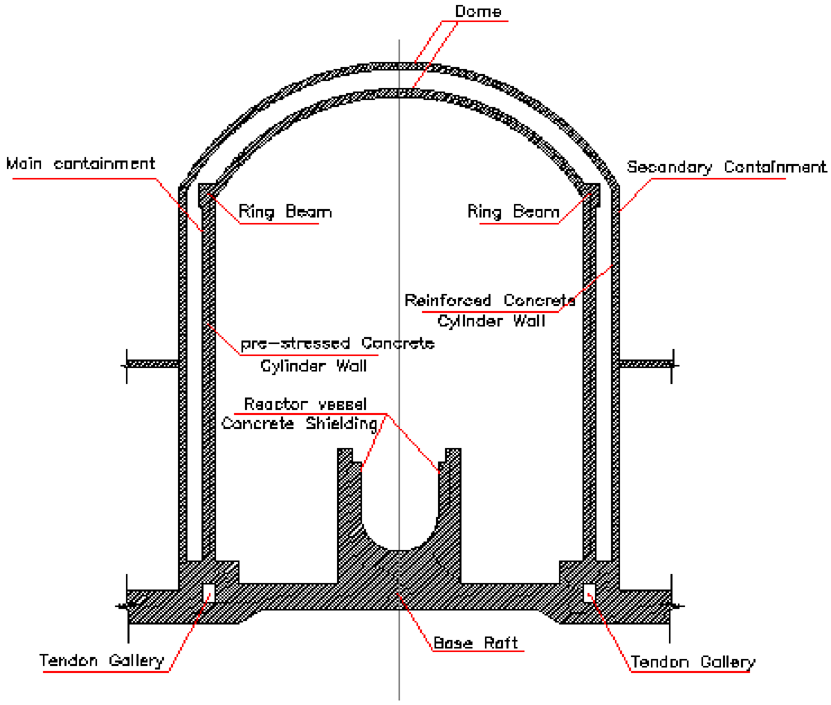


Fig. 5. Arrangement of the Main and Secondary Containment in the Reactor Building [3].

Table 1: Soil Properties [8].

Soil Type	**Height v** (m)	**Radius of foundation R** (m)	**Soil Density ɣ** (kg/m3)	**Wave Velocity S** (m/sec)	**Modulus of Elasticity E** (kg/m2)	**Poisson Ratio ų**	**Friction Angle ϕ_o**	**Shear Modulus G**	**Vertical Stiffness K_{vl}** (kg/m)	**Horizontal Stiffness K_{Hl}** (kg/m)
Clay **S1**	60	58	2002.31	365.76	20394300	0.3	37.5	7843961.54	5866685595.60	3175727800.90
Dense Sand & Gavel **S2**	60	58	2082.4	610	12746452.66	0.3	40	4902481.79	3666682858.22	1984832236.23

Rock (Rhyolite) **S3**	60	58	2482.86	1130	356900674542.27	0.3	60	1372694902 08.57	102667120048 181.00	555753026240 48.20

Table 2: Concrete Properties [9]

Concrete Properties			
Concrete Type	**F_{cu} (Kg/Cm2)**	**γ_c (kg/m3)**	**Modulus of Elasticity Ec (kg/cm2)**
Magnetite	**448**	**3720**	**653013.1**

2.1 Containment Modeling

As shown in Figs. (6), and (7) fixed and isolated base foundations were utilized in the model using solid elements. The fixed base was represented as a circular foundation with 58 m diameter, 7m depth connected to the bottom with soil stiffness springs. Isolated base consists of upper and lower foundation with the same dimensions of the fixed base, and connected to each other with base isolators and the bottom of the lower foundation High Damping Rubber Bearing (HDRB) isolators were used as connectors builders. Their Properties areshown in Figs. (8) where **Kb** is the effective horizontal bearing stiffnessand **KV** is the effective verticalbearing stiffness [12].

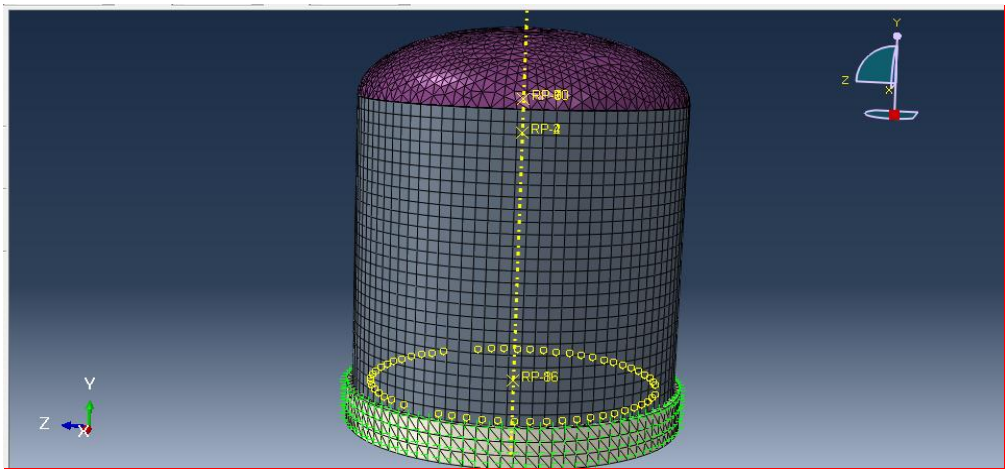


Fig. 6. Arrangement of the Containment in the Reactor Building with Fixed Base on ABAQUS 2023.

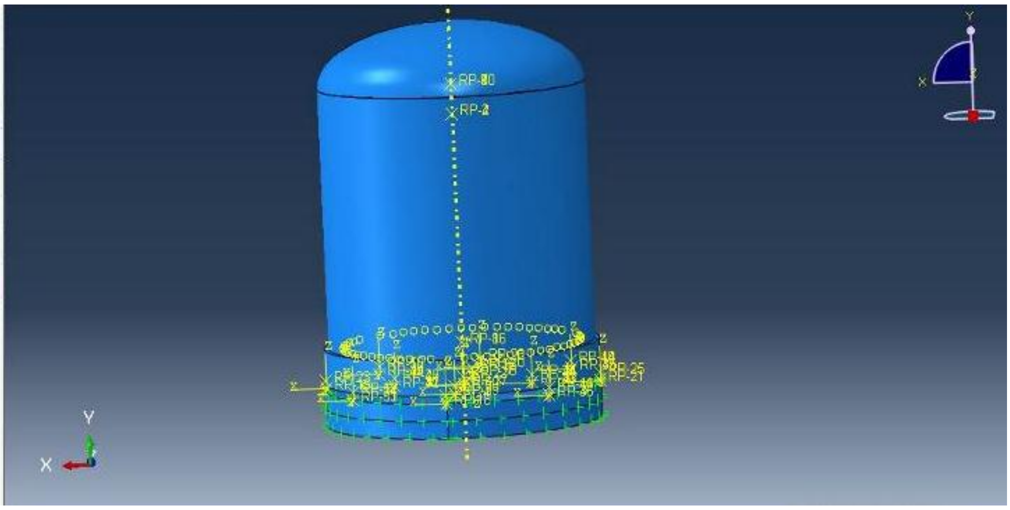


Fig. 7.a. Arrangement of the Containment in the Reactor Building with Isolated Base on ABAQUS 2023.

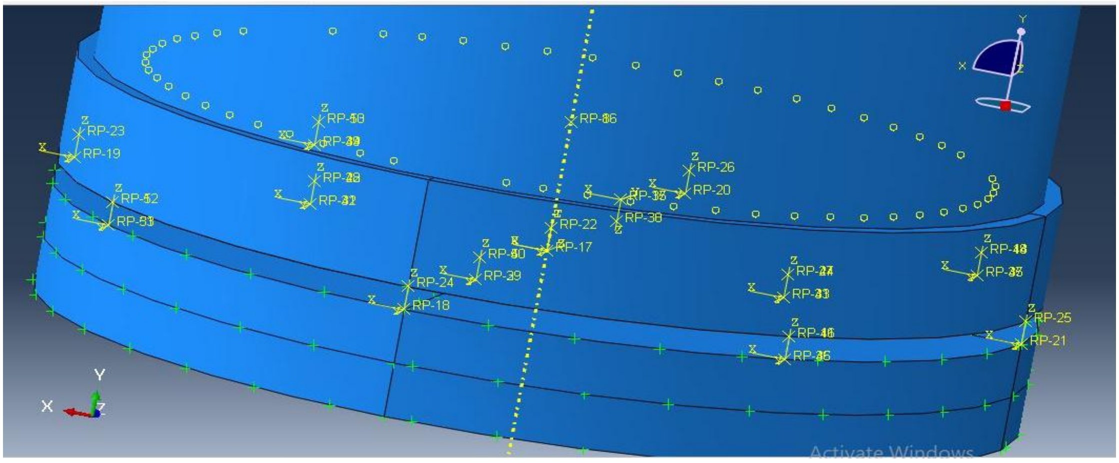
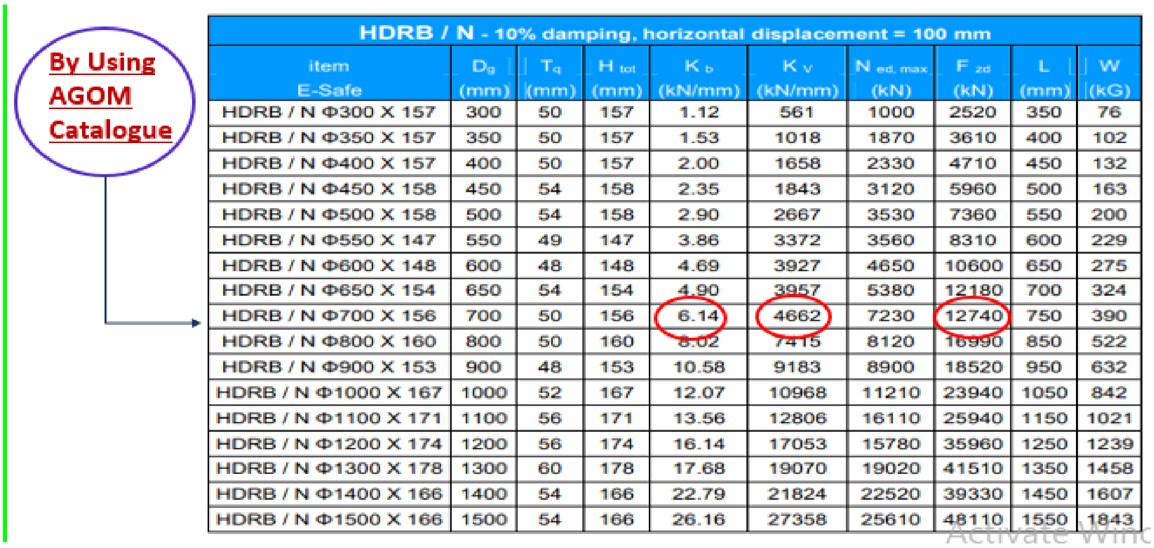


Fig. 7.b. Arrangement of the Upper and Lower Foundation with Isolation in the Reactor Building on ABAQUS 2023.


By Using AGOM Catalogue

HDRB / N - 10% damping, horizontal displacement = 100 mm									
item E-Safe	D_g (mm)	T_q (mm)	H_{tot} (mm)	K_b (kN/mm)	K_v (kN/mm)	$N_{ed, max}$ (kN)	F_{zd} (kN)	L (mm)	W (kG)
HDRB / N Φ300 X 157	300	50	157	1.12	561	1000	2520	350	76
HDRB / N Φ350 X 157	350	50	157	1.53	1018	1870	3610	400	102
HDRB / N Φ400 X 157	400	50	157	2.00	1658	2330	4710	450	132
HDRB / N Φ450 X 158	450	54	158	2.35	1843	3120	5960	500	163
HDRB / N Φ500 X 158	500	54	158	2.90	2667	3530	7360	550	200
HDRB / N Φ550 X 147	550	49	147	3.86	3372	3560	8310	600	229
HDRB / N Φ600 X 148	600	48	148	4.69	3927	4650	10600	650	275
HDRB / N Φ650 X 154	650	54	154	4.90	3957	5380	12180	700	324
HDRB / N Φ700 X 156	700	50	156	6.14	4662	7230	12740	750	390
HDRB / N Φ800 X 160	800	50	160	8.02	7415	8120	16990	850	522
HDRB / N Φ900 X 153	900	48	153	10.58	9183	8900	18520	950	632
HDRB / N Φ1000 X 167	1000	52	167	12.07	10968	11210	23940	1050	842
HDRB / N Φ1100 X 171	1100	56	171	13.56	12806	16110	25940	1150	1021
HDRB / N Φ1200 X 174	1200	56	174	16.14	17053	15780	35960	1250	1239
HDRB / N Φ1300 X 178	1300	60	178	17.68	19070	19020	41510	1350	1458
HDRB / N Φ1400 X 166	1400	54	166	22.79	21824	22520	39330	1450	1607
HDRB / N Φ1500 X 166	1500	54	166	26.16	27358	25610	48110	1550	1843

Fig. 8. Connector Builder Properties [11].

As shown in Fig. (9) the hemispherical concrete dome is pre-stressed by 3 groups of tendons orientated at 60 degrees to each other in plan and anchored in the ring girder. The dimension of the hemispherical concrete dome is 1.3 m thick and 66 m diameter. It was represented in the model as solid elements. Figures. (10), and (11) showthe ring girder used for supporting the dome, and the tendons anchorage in case of vertical tendons and prestressed dome. Typically, the dome is pre-stressed first then the vertical tendons.The dome was represented in the model as solid elements with 6m depth and 2 m width.Buttresses were used in case of Hoop or Circumferential tendons for anchorage. As shown in Figs. (11), and (12) These Buttresses were represented as solid elements in the model with dimensions of 6m depth and 2m width, oriented at 120 degree in the plan to each other, Figs. (13). The secondary containment was represented as a hemispherical reinforced concrete dome supported on reinforced concrete wall; both were represented in the model using solid elements [10].

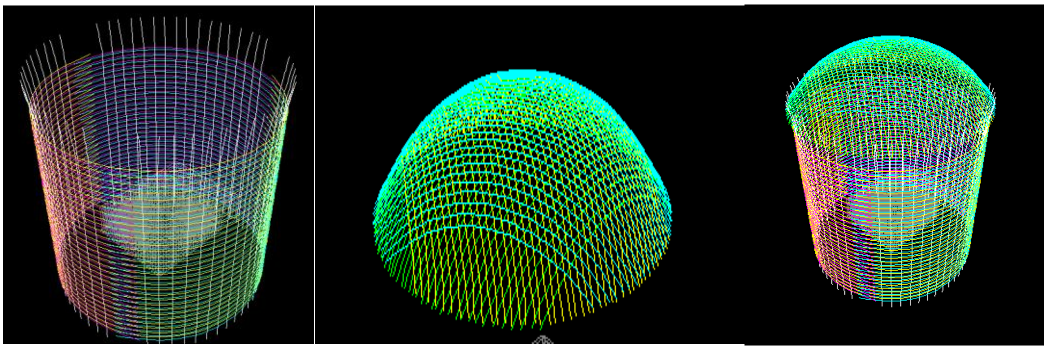


Fig. 9. Main Containment (circumferential – vertical tendons conFig.uration with pre-stressing dome by ABAQUS

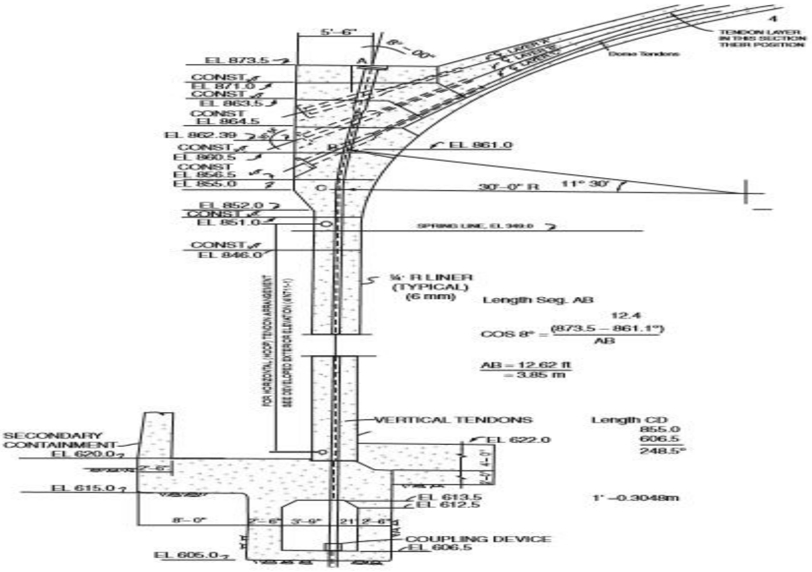


Fig. 10. Dome and Vertical Tendons Anchorage Details [10].

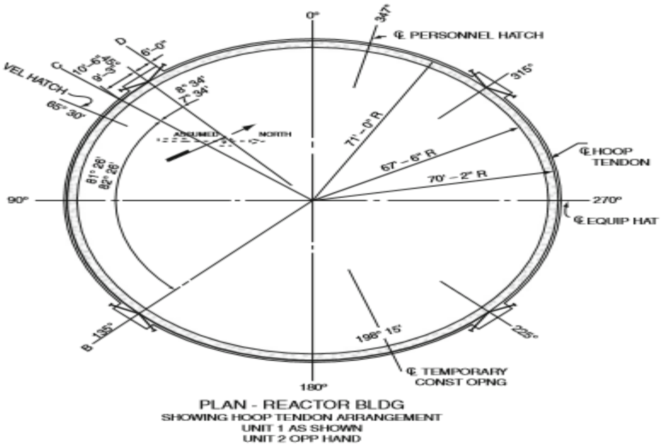


Fig. 11. Hoop Tendons Anchorage Details [10].

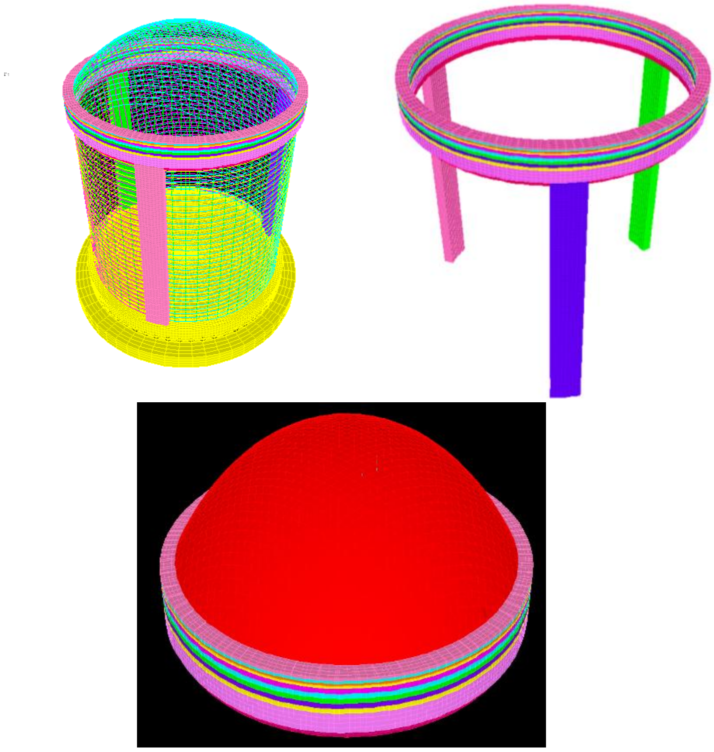
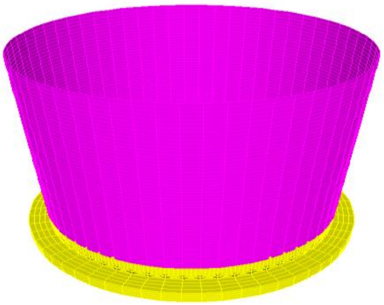


Fig. 12. Hoop and Vertical Tendons with Demonstration of Buttresses and Ring Beam Location



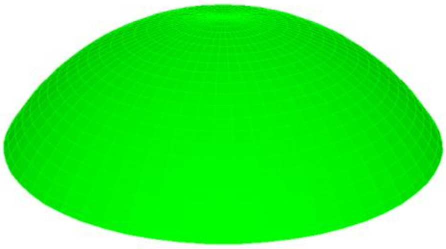


Fig. 13.a Cylinder wall of the secondary containment Fig. 13.b Dome of the secondary containment

2.2Load Combination

As shown in Fig. (14) Time History Analysis was applied by utilizing Elcentro– EQ in X – direction. **Load Combination = D + Pf + Psuction +EQ** Where, **D** is the dead load, **Pf** is the Prestressing force, and **Psuction** is a suction pressure applying on the secondary containment and it is normally taken 0.05 t/m^2**[10].**

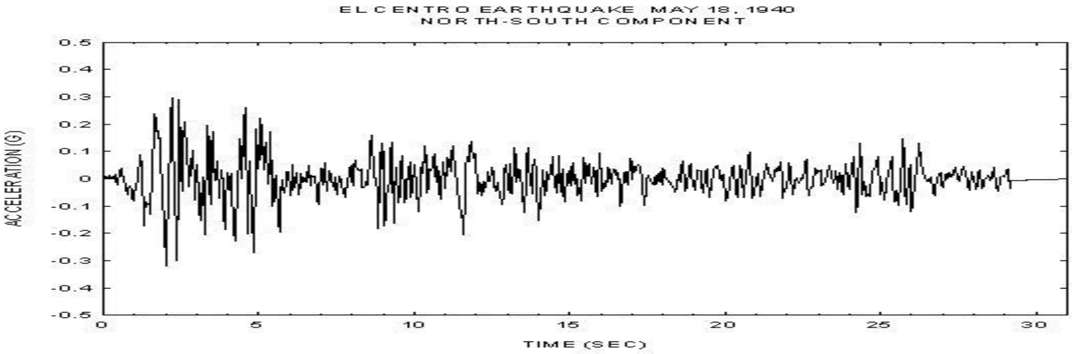


Fig. 14. Elcentro Earthquake [10].

3. RESULTS

The response of power plant structures due to earthquake is represented in numerical and visual outputs that demonstrate the structure behavior under seismic excitation. In case of fixed base, the displacement response is shown in Figs. (15), (16) and (17). At Point (1) located at the interface of foundation and soil, the largest displacement occurred in Rock then Clay and, the smallest value was recorded in dense Sand&Gravel soil. At point (3) the maximum displacement occurred in Clay soil then Rock and dense Sand and Gravel soil. In addition, the difference in displacement value between rock and Sand is negligible. At point (4), the maximum displacement occurred in Clay soil then rock and dense Sand and Gravel soil. In addition, comparingthe relative displacement between points (3and4), Figs. (15) and(19), the highest value recorded in case of Clay soil then rock and dense Sand and Gravel this behavior is attributed to the softness of Clay. All values for the stress's response at point (1) were compression, Figs. (15), (20), (21), and (22). The highest value was recorded in Clay soil then Rock finally dense Sand&Gravel. At point (3), all stresses were tension and the highest stress value was noticed respectively, in clay, rock then dense sand-Gravel and.At point (4) stresses were tension in Clay and compression in rock and sand.

In case of isolated base, the displacement response is shown in Figs. (15), (16), and (17) at point (1) located at the end of upper foundation. Generally, displacement values were less than those in case of fixed base. In addition, the corresponding point which is located at the interface of lower foundation and soil has a very low displacement value compared to that in the fixed base this means that theapplied isolation caused a high energy dissipation for both upper and lower foundation. The same response was recorded for all types of soil. At points (1), (3), and (4), displacement values were equal in all studied types of soilthis means that thesoil type did not affect the structural behavior in the presence of isolation. In addition, for the relative displacement between points (3 and 4), Figs. (15), and (19), all values of the three types of soil were less than the values recorded in fixed base. In addition, the relative displacement values can be neglected due to the stiffer behavior response of the main wall. in Figures. (15), (20), (21), and (22)show the stress response at point (1), (3), and (4). All stress values were tension as the case of base isolation. In addition, the stress values in isolated base case were decreased by 50 to 70 % compared to the fixed base case.

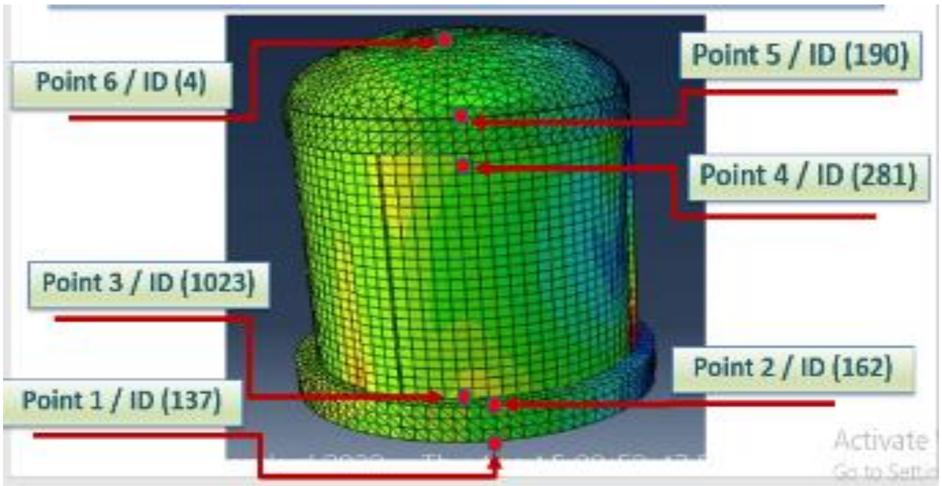


Fig. 15. Points Locations on the Main Containment of the Reactor Building on ABAQUS

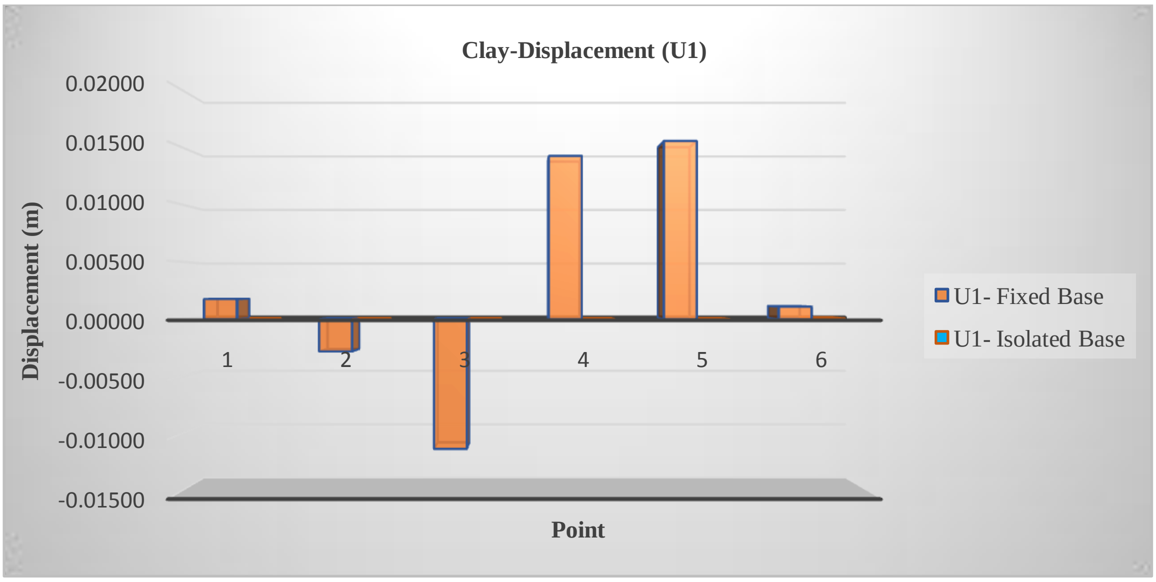


Fig.16. U1 of the Main Containment – Fixed and Isolated Base – Clay Soil - Under Load Combination.

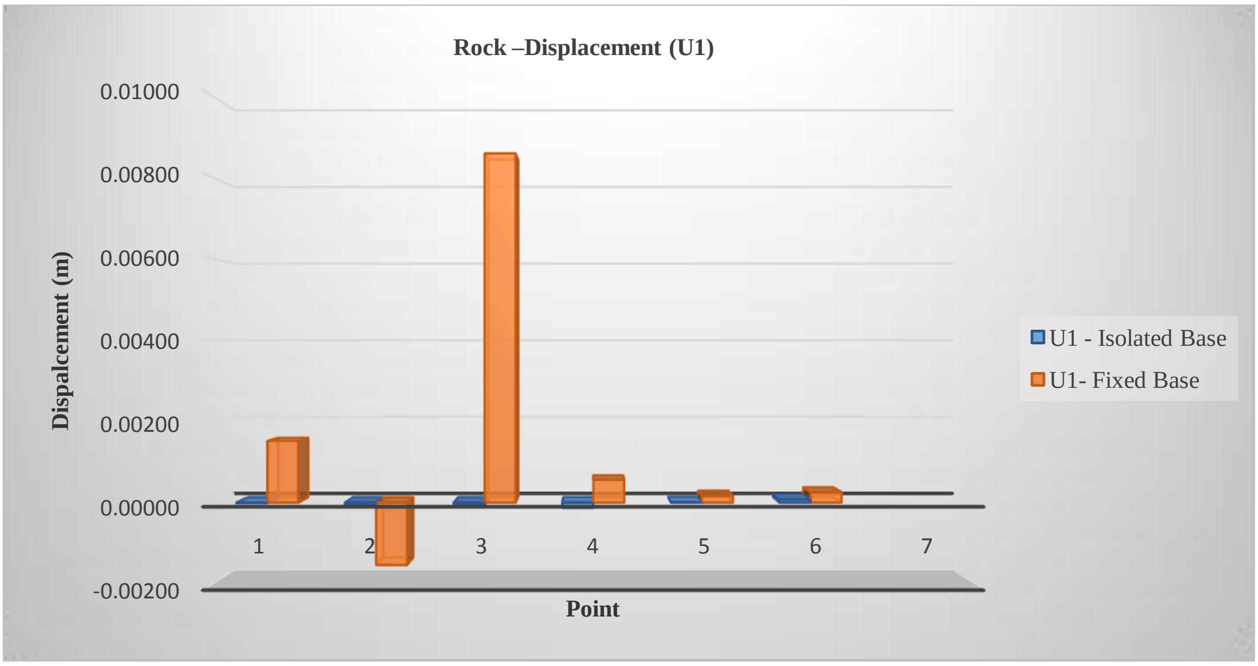


Fig.17. U1 of the Main Containment – Fixed and Isolated Base – Rock Soil - Under Load Combination.

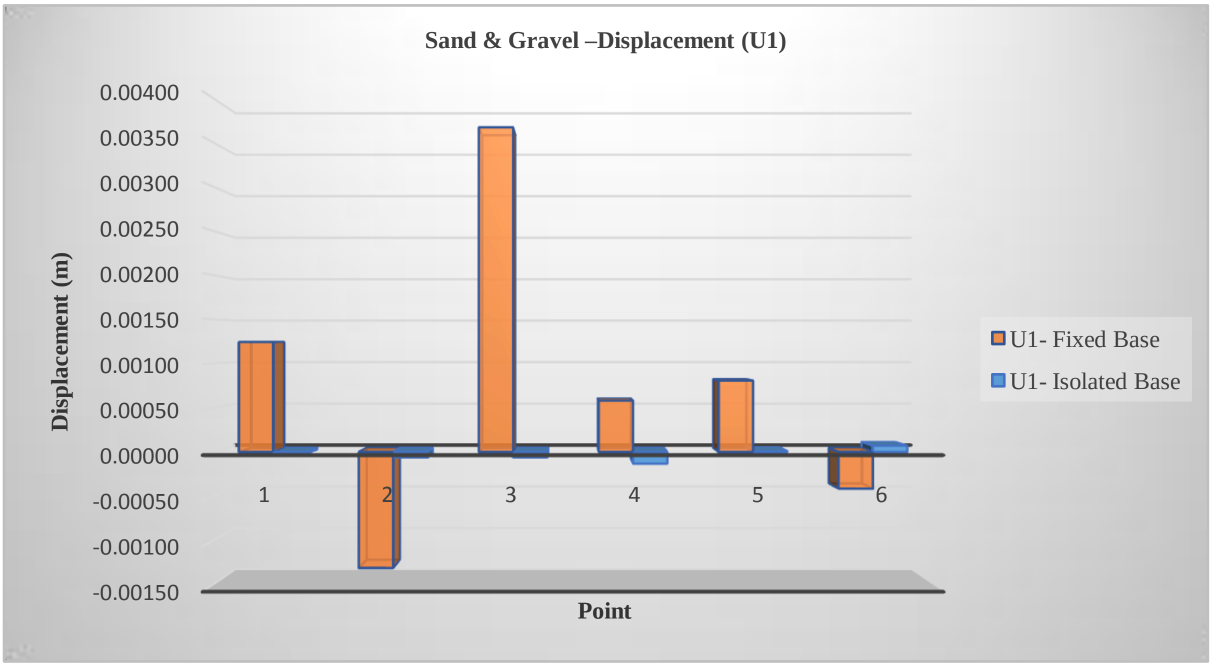


Fig.18. U1 of the Main Containment – Fixed and Isolated Base – Dense Sand andGravel Soil - Under LoadCombination.

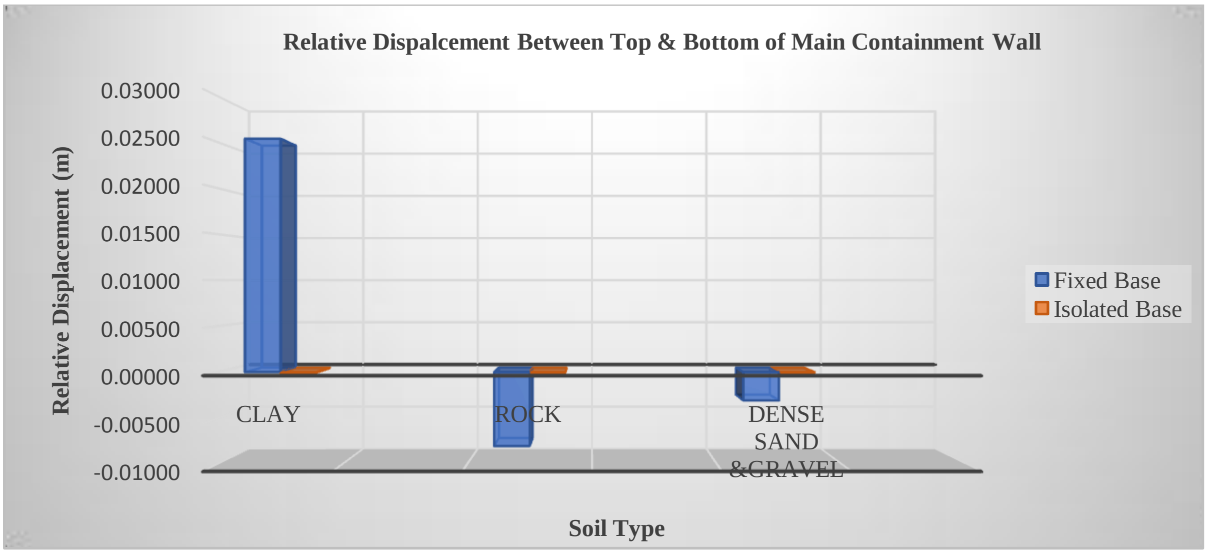


Fig.19. Relative Displacement between Top & Bottom of the Main Containment Wall – Fixed and Isolated Base – Clay,Rock, anddense Sand, andGravel Soil - Under Load Combination.

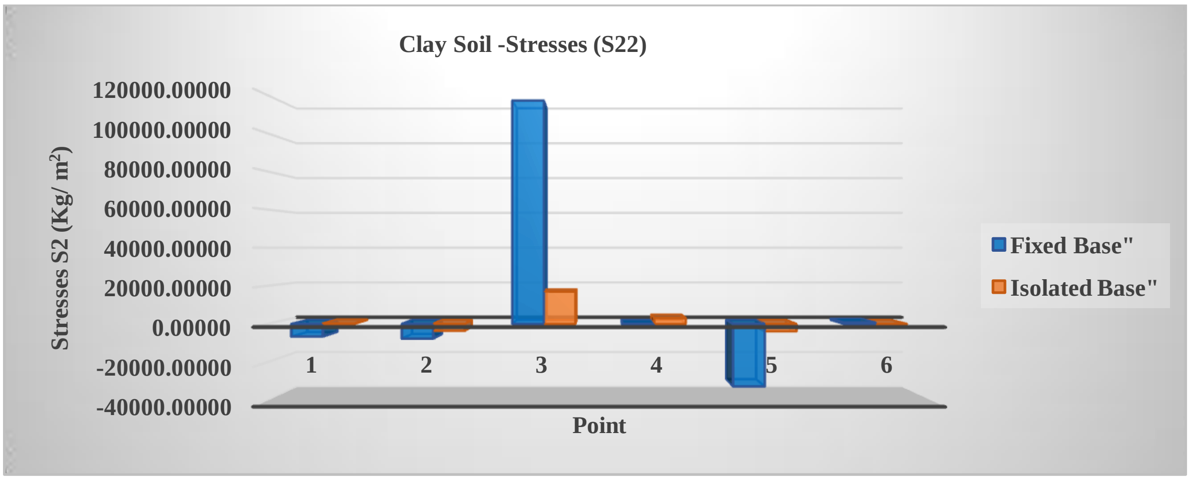


Fig.20. S22 of the Main Containment – Fixed and Isolated Base – Clay Soil - Under Load Combination.

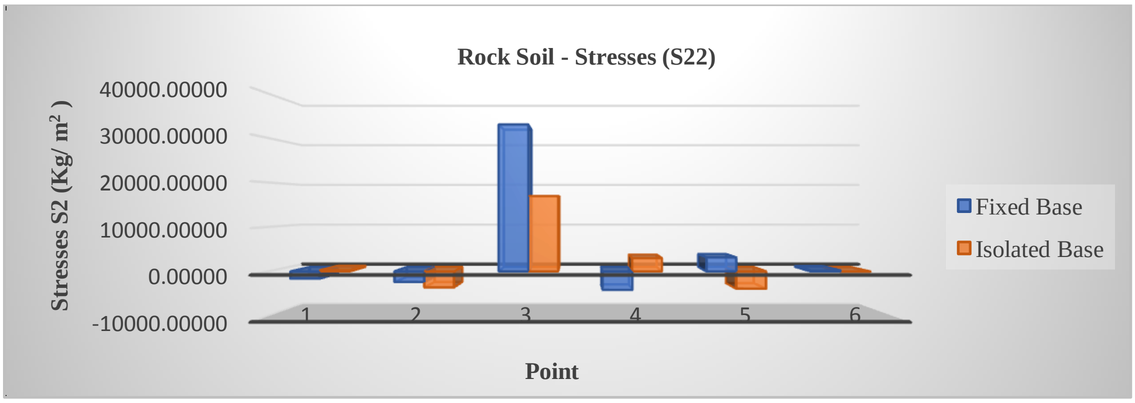


Fig.21. S22 of the Main Containment – Fixed and Isolated Base – Rock Soil - Under Load Combination.

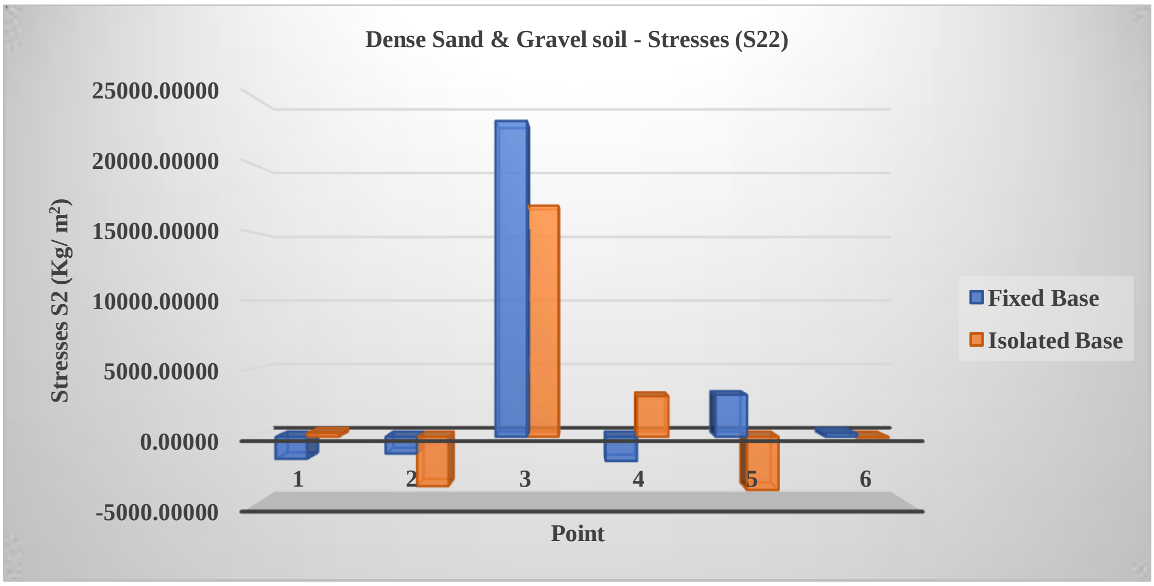


Fig.22. S22 of the Main Containment – Fixed and Isolated Base – dense Sand and Gravel Soil - Under Load Combination.

4. DISCUSION and CONCLUSION

In this research the main containment of external shield of the European pressurized reactor is considered as a case study. The ABAQUS finite element computer program was used to model the containment stresses and displacement response were obtained at critical points in the structure for different types of soils and foundation. Based on the results of this study the following conclusions can be withdrawn:

- InClay soil wherelow stiffness, high shear strain, low seismic wave propagation, plastic deformation, pore pressure effects, and resonance flexible foundation support are induced, Clay exhibits a higher stress response and lower displacement at the foundation-soil interface during seismic events. The highest displacements occurred at the base shear location and at the top of the wall.
- The higher deformation of Clay under seismic forces allows the wall containment to experience high shear deformation, resulting in more significant relative displacements between the top and base.
- In case of Rocksoil, due to the combination of higher stiffness, lower damping,elastic properties and higher wave propagation, greater seismic displacements and lower stresses were recorded at the interface point between the soil and foundation compared to the Clay soil. In addition, due to the wall being stiffer, lower base displacements occurred.
- At the top of the wall Rock soil offers more rigidity and less amplification resulting in smaller relative displacements. In addition, rock limits shear deformation in the wall due to its rigidity, keeping relative displacements smaller.

- The soil properties have critical role in seismic design and performance of the containment in case of isolated base Seismic isolation systems are designed to decouple the superstructure's movement from the ground motion.
- The isolatorssignificantly absorbed and dissipated seismic energy, resulting in reducing the transmission of ground motion to the structure. Accordingly, the interface point between the soil and the foundation exhibits similar displacements and stresses for both Rock and Clay since the isolators dominate the system's response. They decouple the superstructure from ground motion, limit stress transmission, and mitigate soil-dependent effects, ensuring consistent performance across various soil types.This is a key advantage of seismic isolation in ensuring reliable and uniform structural behavior in diverse geological conditions.
- In the presence of isolation stressesand displacements values were equal in all soil types which means that the various of soil types This ensures a perfect performance of the structure, regardless of the underlying soil type.
- In Clay soil the relative displacement between top and base of the wall arises from the soil's flexibility, amplification of seismic waves, and foundation movement.All these factors magnify the dynamic response of the wall.
- In Rock soil, stiffness and rigidity reduce deformation resulting in smaller relative displacements.
- In Clay soil shear deformation was high under seismic forces, resulting in more significant relative displacements between the top and base. In rock soil rock limits shear deformation in the wall due to its rigidity, keeping relative displacements smaller.

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