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Original Article

Structural Performance of RCC Framed Elevated Circular Shape Tank in the Indian Region

Chetan Jaiprakash Chitte[1*], Shrikant Charhate[2], S. Sangita Mishra[3]

[1,2,3]*Amity School of Engineering and Technology, Amity University, Maharashtra, India.*

[*]*Corresponding Author : chetanjchitte@gmail.com*

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***Abstract** - Elevated water storage tanks are pertinent structures, and therefore, ensuring their safety aftershock is vital. Post-shaking must continue to occur to ensure the availability of potable water in quake-affected areas and to meet firefighting requirements. This study focuses on the seismic analysis of RCC-framed circular tanks as per Indian standards. Tank analysis is carried out for four seismic zones with three types of ground conditions according to Indian standards. In the present study, three different water depths, full, half-full and empty tanks, are considered. Tank analysis focuses on determining the peak shear, moment and hydrodynamic pressure. The lateral hydrodynamic impulsive and convective pressure at the base of the wall, wall inertia and pressure due to excitation in a vertical direction is calculated for the tank in full, half-filled condition. The wave height is calculated using horizontal seismic coefficient design in convective mode for four seismic zones and three types of ground conditions as per Indian standards. Tank in full capacity governs the design. For a full capacity of the tank, the horizontal seismic coefficient in convective mode is higher than in impulsive mode, as the time period value is less in impulsive mode. For the same ground conditions, the peak shear and moment values at the bottom of the container are controlled under full tank conditions for seismic zones. These values are 20% greater than those under half-filled conditions and 60% greater than those under empty tank conditions. The impulsive and convective mode seismic coefficients increase with increasing zone and are maximum in the soft soil type. The values of the vertical seismic coefficient increase with increasing zone and remain the same for all three types of soil conditions. The values of hydrodynamic maximum pressure, hydrodynamic impulsive lateral pressure on the base, hydrodynamic convective pressure on the base and wall inertia pressure in tank full case are 30% greater in soft soil type, 33% greater in medium stiff soil; additionally, the values are 38% greater in rocky or hard soil than in half-filled tank.*

***Keywords** - Circular elevated tank, Impulsive mode, Convective mode, Seismic analysis for maximum base shear, Maximum base moment, Seismic horizontal and vertical coefficient, Hydrodynamic pressure.*

1. Introduction

Elevated water storage tanks are structures of prime importance; therefore, ensuring their safety post-earthquake is vital. Post-shaking must continue to occur to ensure the availability of potable water in earthquake-affected areas and to meet firefighting requirements.

Designing an elastic structure is not cost-effective, and it is difficult to justify infrequent earthquake loads [9, 10]. Rather, conventional practice allows some structural and non-structural damage to occur during severe earthquakes if the structure does not collapse. The main basis of the construction of structures for strong earthquakes is their non-collapse [4, 6, 7].

However, allowable damage is allowed for structural components. Suppose a structure exposed to a severe earthquake is allowed to deteriorate. In that case, the seismic force will be less than expected in a strong earthquake if the seismic force remains linearly elastic [8, 10]. Response modification /reduction factor (R) reduces the actual value of base shear to the required design lateral strength [11, 17-20]. For elastic structures, design base shear is calculated by dividing it twice 'R' as per Indian standard for seismic analysis [1-3].

Thus, the factor 'R' indicates the predicted degree of excess strength and ductility for the structure [12, 13]. As a result, by considering the elements, greater strength, redundancy and ductility factor, the structure can be built for much lesser force than predicted by intense shaking, which prevents the collapse of the structure. The values of base shear, base moment and hydrodynamic pressure are verified for different ground conditions [16].

During an earthquake, water vibrates in two opposite directions as impulsive and convective masses. The amount of water that vibrates with the container is the impulsive mass, and the one that moves opposite to the container is the convective mass. Along with mass momentum, fluid displacement also contributes to hydrodynamic forces. There are two ways to model water in a tall water tank with a solid container [5-7]: a single-Degree-of-Freedom (DOF) system and a two-DOF system.

The older Indian code IS 1893 considers a 1-DOF system, whereas the revised Indian code IS 1893 proposed a 2-DOF system for modelling. Along with the modelling approach, the response reduction factor value has also been revised. In the older code, for calculation of base shear performance factor (K) is used, but no such factor for water tanks [21].

A 'K' factor of 1.0 has been used for ductile buildings, and it is a latent consideration that the behaviour of elevated water tanks will be similar to ductile building frames, which is irrational. In the revised IS 1893 'R' factor of 5 is used for buildings with ductile detailing, so it can be considered that the older IS 1893 code uses an approximate 'R' factor of 5.

A single DOF system considers water together with the mass of the structural container and the mass of the staging as an impulsive mass. In 1963, Housner [5] proposed a two-DOF system approach, in which the mass, together with the mass of the container and the mass of the staging, are considered as equivalent mechanical models corresponding to the first DOF, the convective mass as the second DOF. In this model, the convective and impulsive components constitute hydrodynamic force [14, 15].

2. Methodology

2.1. Maximum Base Shear

The Indian code considers impulse and convective modes for elevated tanks. According to Indian Standard 1893_2 [3], the maximum base shear 'V' for elevated tanks is determined by considering horizontal shear at the base in impulse (Vi) and convective (Vc) modes. 'R' values for water tanks [11, 17-20] varies between 2 to 4.

2.2. Maximum Base Moment

According to Indian Standard 1893_2 [3], the total overturning moment at base 'M' is given by combining the impulsive (M_i) and convective mode moment (M_c).

2.3. Calculation of Hydrodynamic Pressure

2.3.1. Determination of Combined Pressure (Hydrodynamic)

During the ground shaking, lateral and vertical hydrodynamic pressure are applied to on wall of the tank and the base of the tank [3, 15].

2.3.2. Impulsive Hydrodynamic Pressure

For circular tanks, water exerts the impulsive hydrodynamic pressure at the tank wall and bottom. Figure 1 shows the typical geometry of a circular tank for determining impulsive and convective pressure.

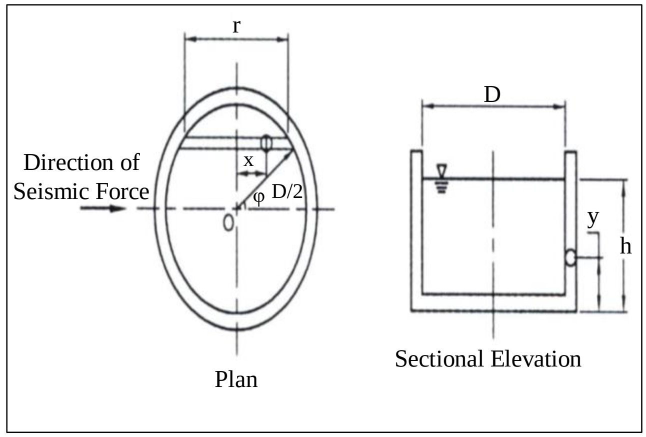


Fig. 1 Typical geometry of circular tank for calculating impulsive & convective pressure [3]

The pressure is maximum when circumferential angle, ϕ=0 and y =0, at the bottom of the wall. Figures 2 to 8 show parameters for modelling of spring-mass for the circular tank.

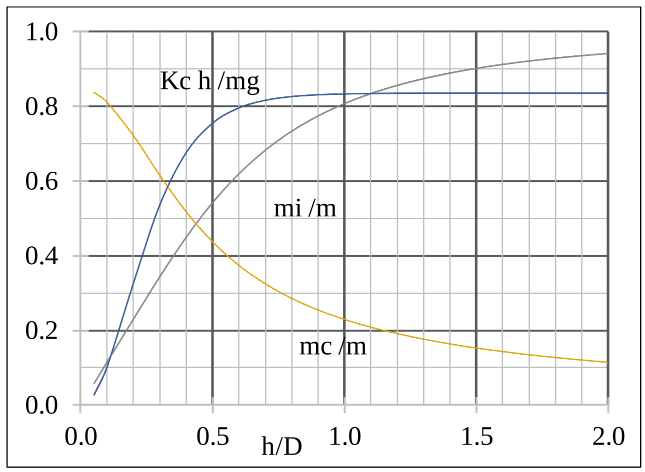


Fig. 2 Impulsive (mi) and convective (mc), spring stiffness convective mode (kc) with a maximum depth of water (h) [3]

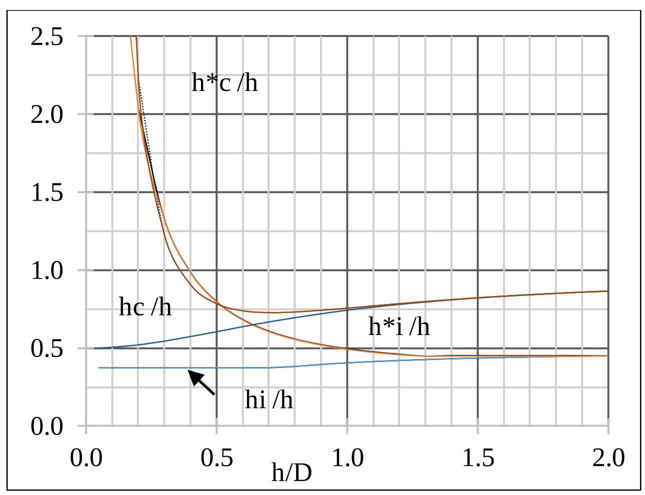


Fig. 3 Impulsive (hi) and convective (hc) masses heights without and with (h*i & h*c) consideration of base pressure [3]

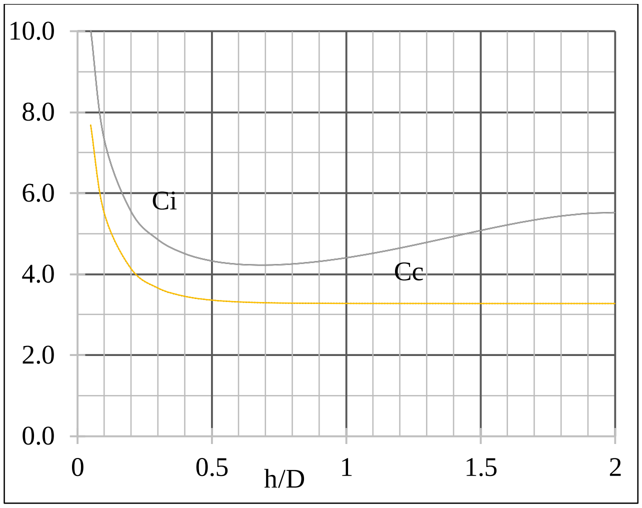


Fig. 4 Time period coefficient in impulsive (Ci) and convective (Cc) mode for circular tank [3]

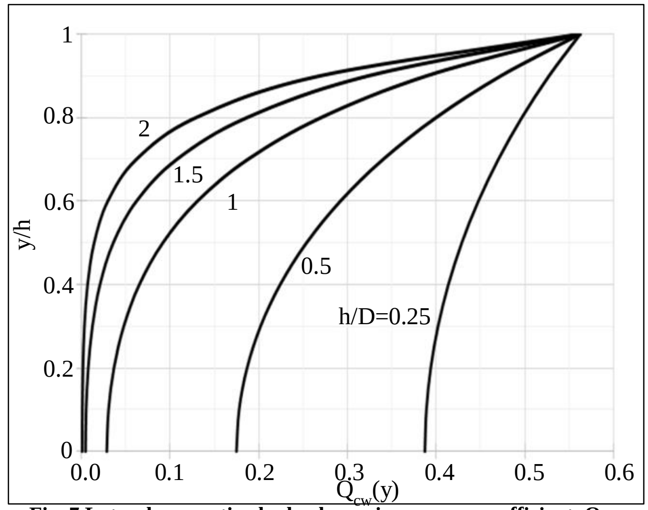


Fig. 7 Lateral convective hydrodynamic pressure coefficient, Qcw on wall of circular tank [3]

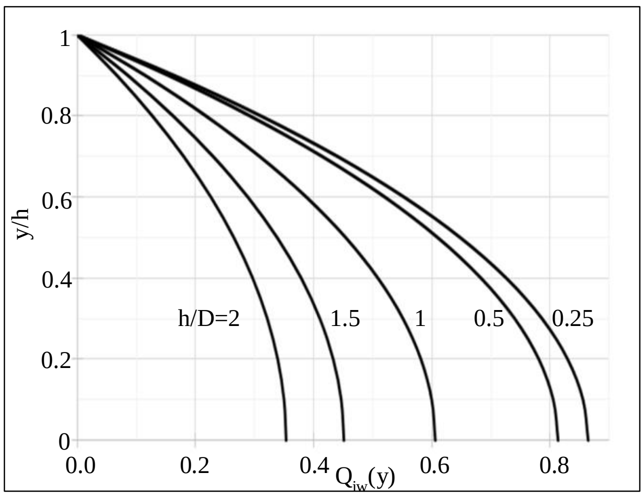


Fig. 5 Hydrodynamic pressure coefficient, Qiw on wall of circular Tank in lateral direction in impulsive mode [3]

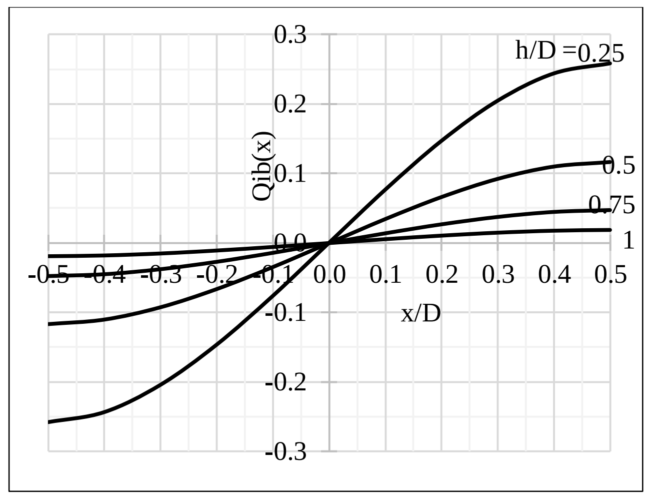


Fig. 8 Vertical convective hydrodynamic pressure coefficient, Qcb on base of circular tank [3]

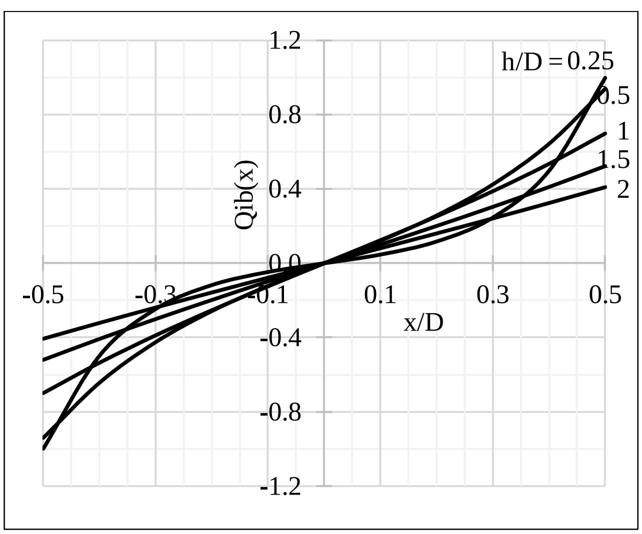


Fig. 6 Hydrodynamic pressure coefficient, Qib on base of circular tank in vertical direction in impulsive mode [3]

2.3.3. Hydrodynamic Pressure of Convective Mode

The convective pressure is exerted by the oscillating liquid on the tank wall and base.

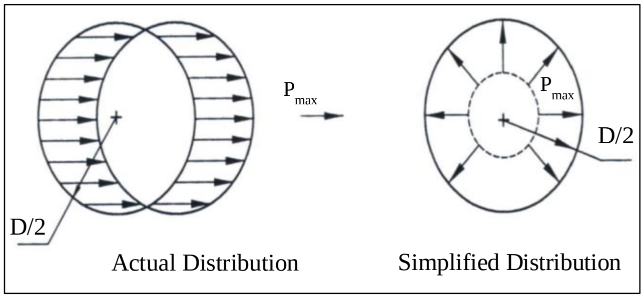
2.3.4. Wall Inertia Pressure

The pressure on the tank wall due to its inertia is uniformly distributed along the height of the wall.

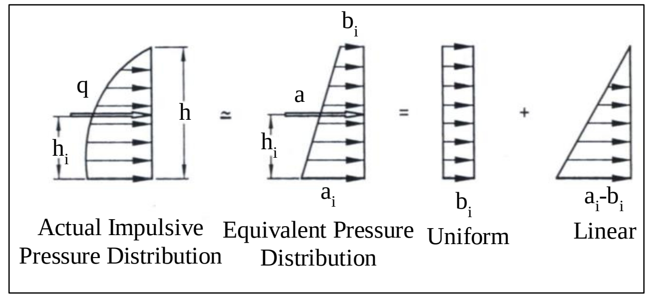
2.3.5. Vertical Excitation Pressure

The effective weight of liquid increases due to vertical ground acceleration, which contributes to subsidiary pressure on the tank wall. This pressure distribution is the same as that of hydrostatic pressure.

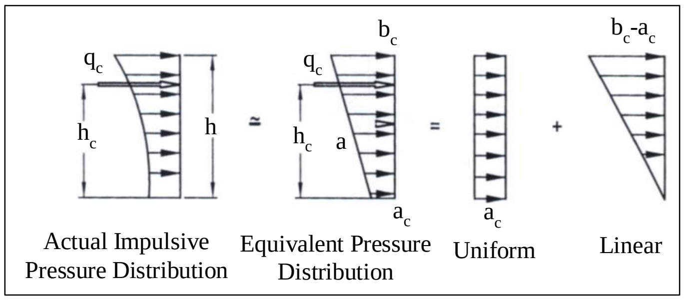
In the calculation of pressure on the tank wall due to vertical acceleration, the vertical seismic coefficient is taken as two-thirds of the maximum horizontal seismic coefficient. The time period in the vertical mode of vibration for tanks is recommended to be 0.3 seconds. [3]



(a) Distribution of pressure in circumferential direction on the wall tank



(b) Equivalent linear variation in the impulsive pressure along the height of the wall



(c) Equivalent linear variation of convective pressure along the height of the wall

Fig. 9 Distribution of hydrodynamic pressure for wall analysis on wall and base [3]

2.3.6. Determination of Maximum Hydrodynamic Pressure

The maximum hydrodynamic pressure is evaluated by combining the pressure due to horizontal and vertical excitation.

2.3.7. Determination of Sloshing Wave Height

The maximum sloshing wave height for a circular tank is calculated as the convective mode seismic coefficient in the horizontal directions times half the container diameter. The maximum value of the wave sloshing height is the deciding parameter for freeboard provision. This provision governs tanks containing toxic liquids where liquid loss must be prevented. For insufficient freeboard, the roof structure is designed to resist uplift fluid displacement pressure.

3. Description of Tank

This study focused on the seismic analysis of RCC circular tanks as per IS 1893 (Part-2): 2014 for a total capacity of 2 Lakh Liters. The cross section of the tank is circular with a diameter of 7.5m and a height of storage of 5m with 0.3m freeboard. The tank has s framed supported structure in which columns are connected by bracings at regular intervals of 4m, as shown in Figure 5. The tank analysis is carried out for four seismic zones [Zone II to V] with three types of ground conditions according to Indian standards.

Tank analysis focuses on the determination of the peak shear and moment values of maximum hydrodynamic pressure. Lateral hydrodynamic impulse and convective pressure at the base of the wall, wall inertia and pressure due to excitation in the vertical direction are calculated for the tank in full, half-filled condition. The wave height is calculated using horizontal seismic coefficient design in convective mode for four seismic zones and three types of ground conditions as per Indian standards. For impulsive mode, a damping value of 5% and for convective mode, 0.5% is considered for the RCC tank [22]. The value of R is taken as 4.

Table 1. Geometrical details for 200m^3 ESR

Capacity of Container	200000 Liters
Diameter of Container	7.5 m
Height of Container	5 m
Freeboard	0.3 m
Wall Thickness of the Container	200 mm
Thickness of the Roof Slab	150 mm
Thickness of Floor Slab	200 mm
Height of Staging	18 m
Depth of Foundation	2 m below G.L
Column Diameter	600 mm
Floor Beams	300 mm x 600 mm
Brace	300 mm x 450 mm
Length of Column	3 m
No. of Columns	6

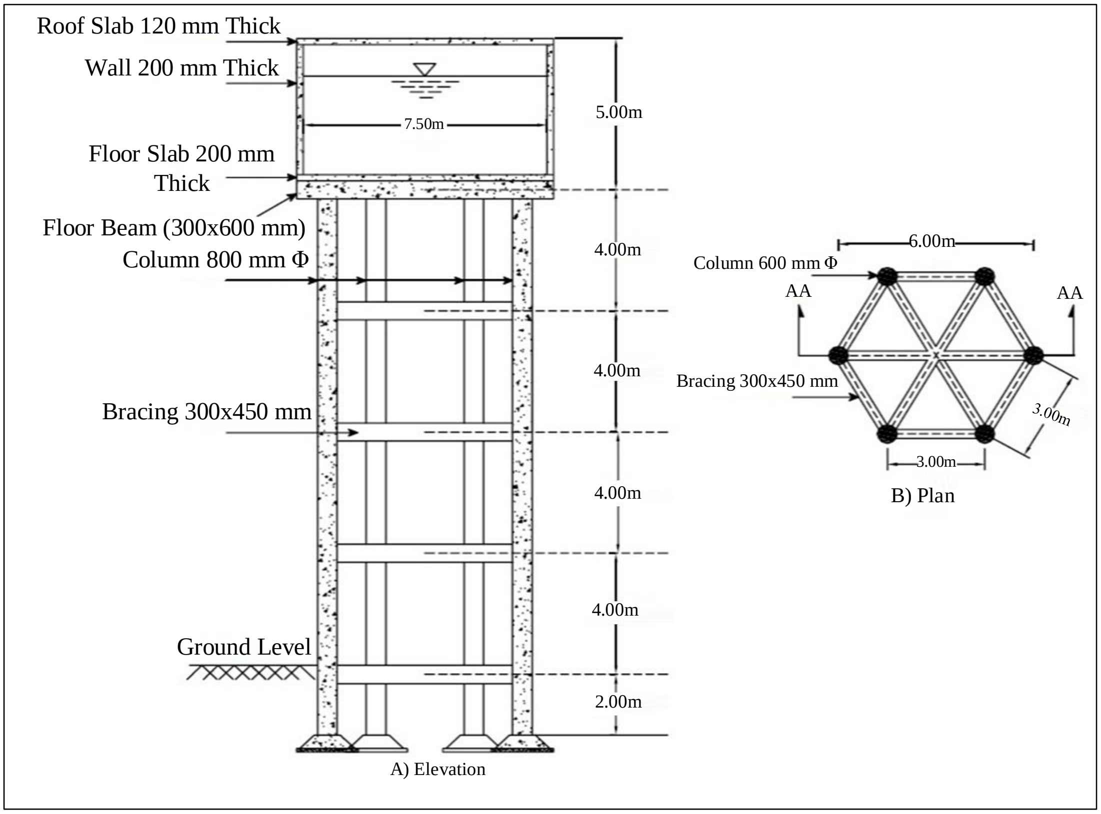


Fig. 10 Circular water tank

4. Results and Discussion

The maximum shear and overturning moment at the base of the container are evaluated under different zone factors, soil conditions, and full, half-filled and empty tank conditions. Tables 2, 3 and 4 summarize the various calculated parameters. The pressure due to horizontal and vertical excitation are combined to obtain maximum hydrodynamic pressure. The wave height is calculated using horizontal seismic coefficient design in convective mode for four seismic zones with three types of ground conditions according to Indian standards. The analysis revealed that full tank conditions govern the design of the tank.

Table 2. Analysis of tank full

Condition-Tank Full												
Soil	Soil Type-Rocky or Hard				Soil Type-Medium Stiff				Soil Type-Soft			
Seismic Zones	II	III	IV	V	II	III	IV	V	II	III	IV	V
Ahi	0.0182	0.0291	0.0437	0.0656	0.0248	0.0396	0.0595	0.0892	0.0304	0.0487	0.0730	0.1095
Ahc	0.0112	0.0180	0.0270	0.0404	0.0153	0.0244	0.0367	0.0550	0.0188	0.0300	0.0450	0.0675
Av	0.0313	0.0500	0.0750	0.1125	0.0313	0.0500	0.0750	0.1125	0.0313	0.0500	0.0750	0.1125
Maximum Shear at base (kN)	59	94	141	211	80	128	191	287	98	157	235	352
Maximum Moment at base (kN.m)	1188	1900	2850	4275	1615	2584	3876	5814	1983	3173	4760	7140
Impulsive Hydrodynamic Pressure, Piw (kN/m^2)	0.64	1.03	1.54	2.31	0.87	1.40	2.09	3.14	1.07	1.71	2.57	3.85
Convective Hydrodynamic Pressure, Pcw (kN/m^2)	0.29	0.46	0.69	1.04	0.39	0.63	0.94	1.41	0.48	0.77	1.16	1.73
Pressure due to wall inertia, Pww (kN/m^2)	0.09	0.15	0.22	0.33	0.12	0.20	0.30	0.45	0.15	0.24	0.37	0.55
Pressure due to Vertical Excitation, Pv (kN/m^2)	1.44	2.31	3.46	5.19	1.44	2.31	3.46	5.19	1.44	2.31	3.46	5.19
Maximum hydrodynamic Pressure, P (kN/m^2)	1.64	2.63	3.94	5.92	1.79	2.87	4.31	6.46	1.95	3.12	4.68	7.02
Sloshing Wave Height(m), dmax = (Ah)c x D/2	0.04	0.07	0.10	0.15	0.06	0.09	0.14	0.21	0.07	0.11	0.17	0.25

Table 3. Analysis of tank half-filled

Condition-Tank Half-Filled												
Soil	Soil Type-Rocky or Hard				Soil Type-Medium Stiff				Soil Type-Soft			
Seismic Zones	II	III	IV	V	II	III	IV	V	II	III	IV	V
Ahi	0.0206	0.0329	0.0494	0.0741	0.0280	0.0448	0.0671	0.1007	0.0344	0.0550	0.0824	0.1237
Ahc	0.0112	0.0180	0.0270	0.0404	0.0153	0.0244	0.0367	0.0550	0.0188	0.0300	0.0450	0.0675
Av	0.0313	0.0500	0.0750	0.1125	0.0313	0.0500	0.0750	0.1125	0.0313	0.0500	0.0750	0.1125
Maximum Shear at base (kN)	49	78	117	176	66	106	159	239	82	130	196	294
Maximum Moment at base (kN.m)	968	1549	2323	3484	1316	2106	3159	4738	1616	2586	3879	5819
Impulsive Hydrodynamic Pressure, Piw (kN/m^2)	0.43	0.69	1.04	1.56	0.59	0.94	1.41	2.12	0.72	1.15	1.73	2.60
Convective Hydrodynamic Pressure, Pcw (kN/m^2)	0.42	0.67	1.01	1.51	0.57	0.91	1.37	2.05	0.70	1.12	1.68	2.52
Pressure due to wall inertia, Pww (kN/m^2)	0.10	0.16	0.25	0.37	0.14	0.22	0.34	0.50	0.17	0.27	0.41	0.62
Pressure due to Vertical Excitation, Pv (kN/m^2)	0.77	1.23	1.84	2.76	0.77	1.23	1.84	2.76	0.77	1.23	1.84	2.76
Maximum hydrodynamic Pressure, P (kN/m^2)	1.02	1.64	2.46	3.69	1.20	1.92	2.88	4.32	1.37	2.19	3.29	4.93

Table 4. Analysis of tank empty

Condition-Tank Empty												
Soil	Soil Type-Rocky or Hard				Soil Type-Medium Stiff				Soil Type-Soft			
Seismic Zones	II	III	IV	V	II	III	IV	V	II	III	IV	V
Ahi	0.0248	0.0397	0.0595	0.0893	0.0337	0.0540	0.0810	0.1215	0.0414	0.0663	0.0994	0.1492
Ahc	0.0112	0.0180	0.0270	0.0404	0.0153	0.0244	0.0367	0.0550	0.0188	0.0300	0.0450	0.0675
Av	0.0313	0.0500	0.0750	0.1125	0.0313	0.0500	0.0750	0.1125	0.0313	0.0500	0.0750	0.1125
Maximum Shear at base (kN)	37	59	88	132	50	80	120	179	61	98	147	220
Maximum Moment at base (kN.m)	736	1177	1766	2648	1000	1601	2401	3602	1228	1966	2948	4423

The design value of the seismic lateral coefficient in convective mode is higher than in impulse mode in full tank conditions due to the lesser value of the time period in the impulse mode. Maximum shear and overturning moment values at the base of the container are governed under full tank conditions compared to half-filled and empty tank conditions for the same ground conditions in different zones.

In tank full condition, values of seismic horizontal coefficient in the convective mode (Ahc) are higher than in impulsive mode (Ahi) due to lower values of the time period in impulsive mode.

In impulsive mode, as compared with full tank condition, the lateral seismic coefficient increases for half-filled and empty tanks. The values of the lateral seismic coefficient in the impulsive mode are greater than those in the convective mode for a half-filled tank. This is due to the lower values of the impulsive mass of liquid.

The mass of water is less for a half-filled tank than for a full tank]. Values of seismic horizontal coefficient in the impulsive and convective mode increase as the zone factor increases [zone II to V] for the same soil condition. Values of seismic horizontal coefficient in impulsive and convective mode increase for higher zones as ground conditions change from Rocky to medium stiff to soft soil.

The values of maximum lateral shear at base govern in the tank full condition than the tank half-filled and tank empty conditions. The values of maximum shear at the base govern seismic zone V. Maximum shear values at the base govern in Type-1 soil (rocky hard) conditions than with type-2 (medium stiff) and type 3 (soft) soil conditions.

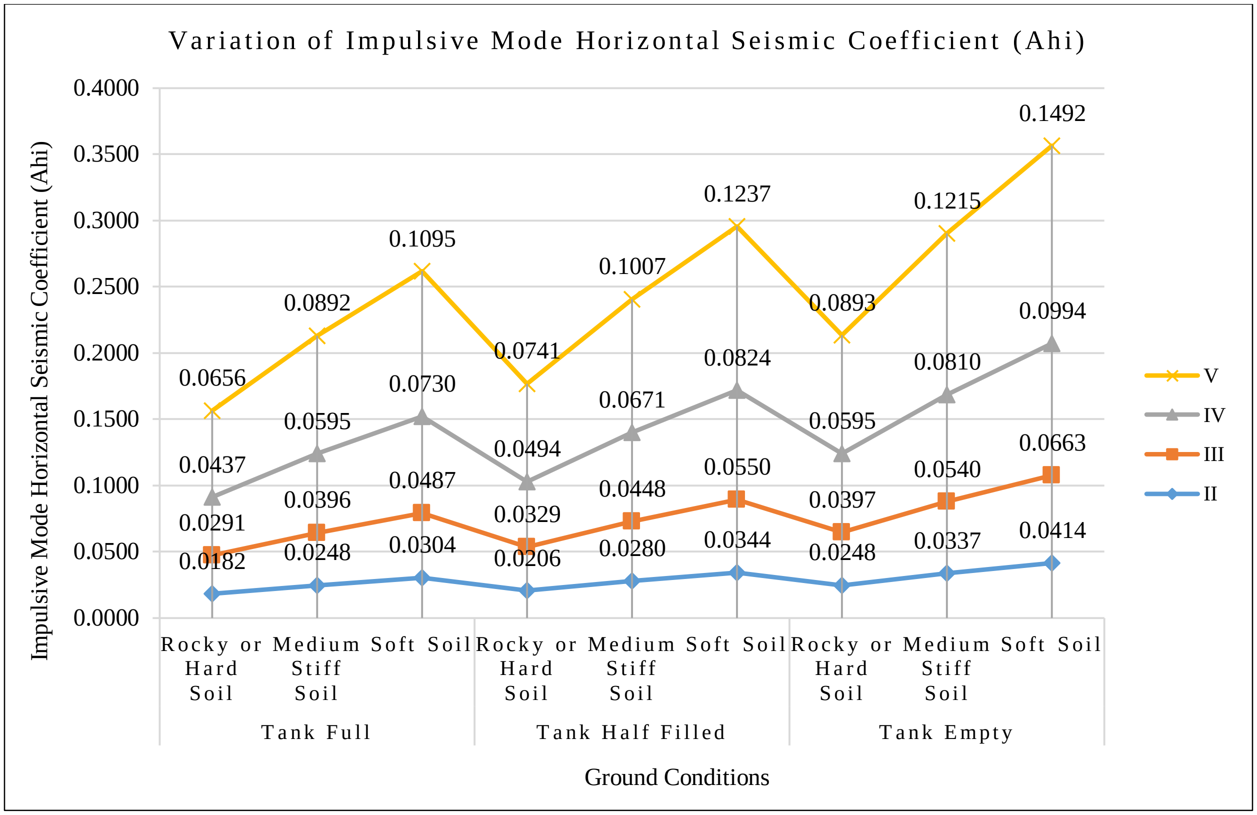


Fig. 11 Variation of impulsive mode horizontal seismic coefficient

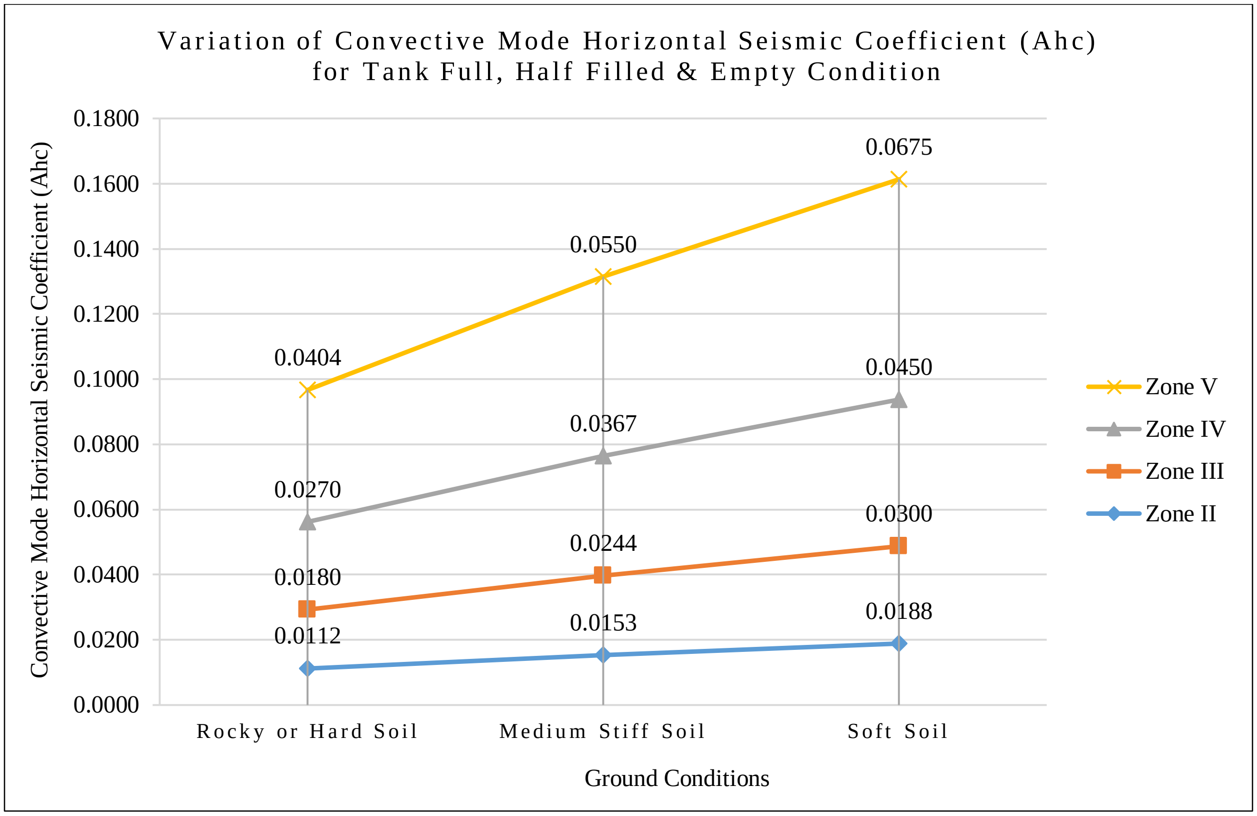


Fig. 12 Variation of convective mode horizontal seismic coefficient

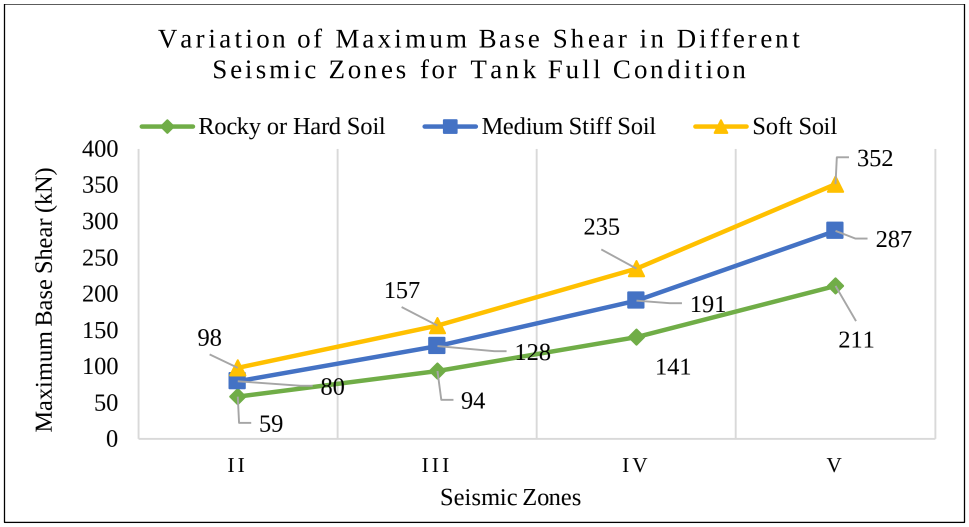


Fig. 13 Base shear variation for full tank

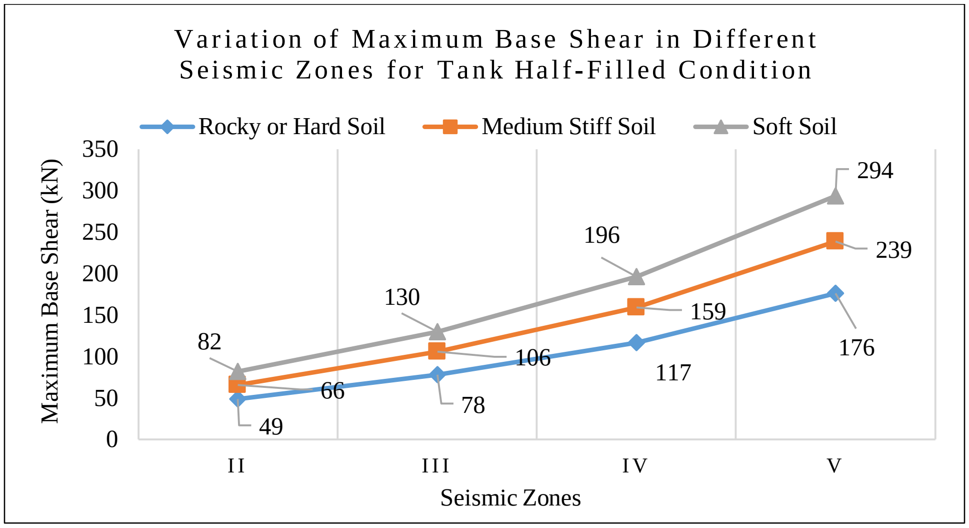


Fig. 14 Base shear variation for half-filled tank

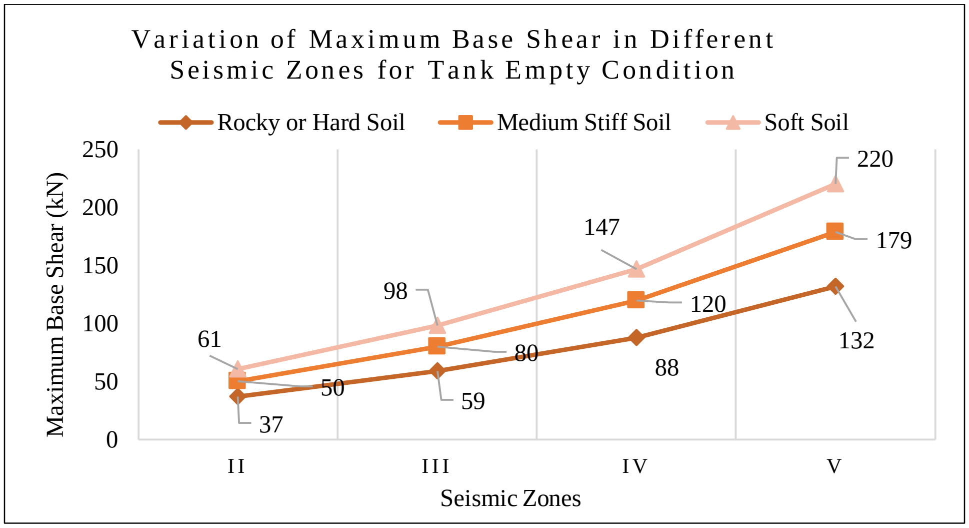


Fig. 15 Base shear variation for empty tank

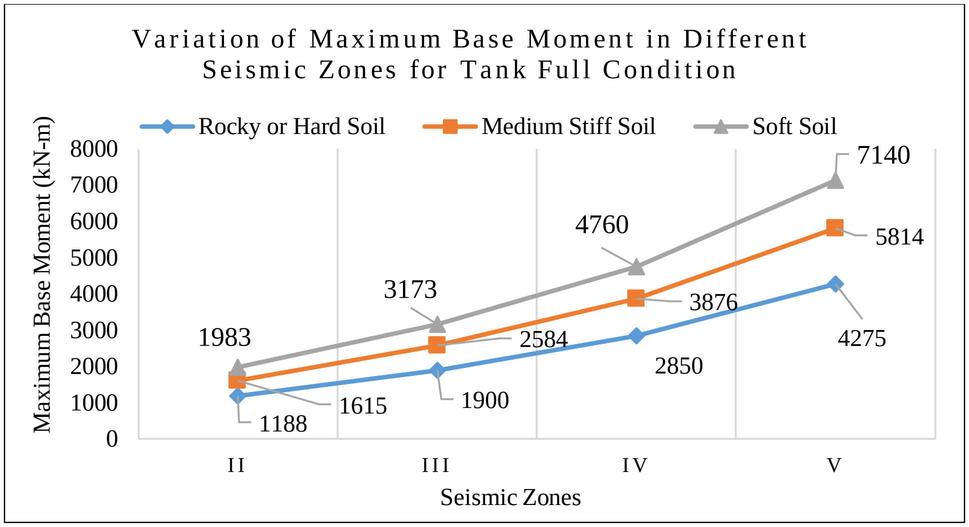


Fig. 16 Base moment variation for full tank

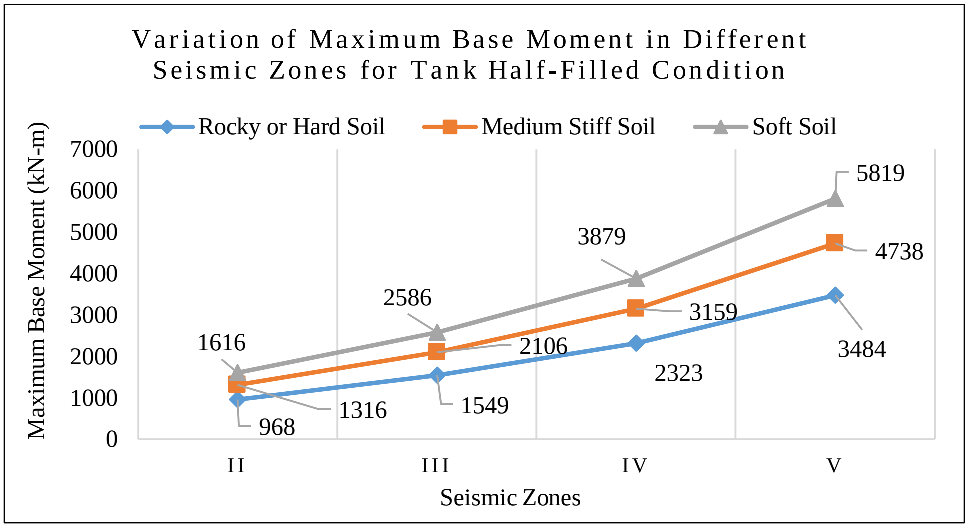


Fig. 17 Base moment variation for half-filled tank

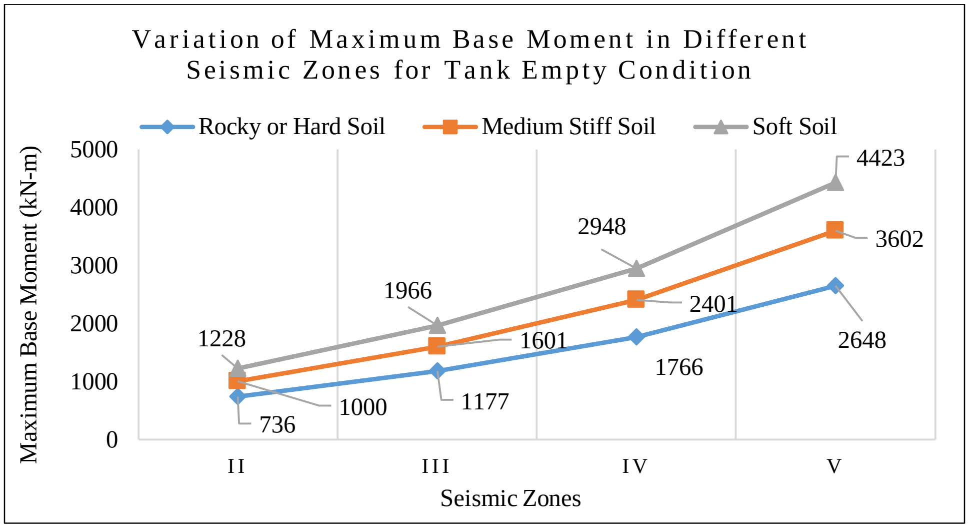


Fig. 18 Base moment variation for empty tank

The maximum overturning moment at base governs in the tank full condition than half-filled and empty tank conditions. Maximum moment values at the base govern in the seismic zone V. Maximum moment values at the base are governed in Type-1 soil (rocky hard) conditions than with type-2 (medium stiff) and type 3 (soft) soil conditions. The values of maximum hydrodynamic pressure (P) govern the higher seismic zone with a soft soil type. Values of hydrodynamic maximum pressure (P), hydrodynamic impulsive lateral pressure (Piw), hydrodynamic convective pressure (Pcw) on the base of the wall and wall inertia pressure (Pww) in full tank condition are 30% more in soft soil type, 33% in Medium Stiff Soil and 38% more in Type-1 soil (rocky hard) as compared with tank half-filled condition. The sloshing wave height governs the higher seismic zone with a soft soil type. The value of the freeboard to be provided shall be in accordance with the maximum sloshing wave height. It shall not be less than the maximum sloshing wave height. Maximum hydrodynamic pressure calculations govern the tank full conditions as compared with the tank half-filled condition.

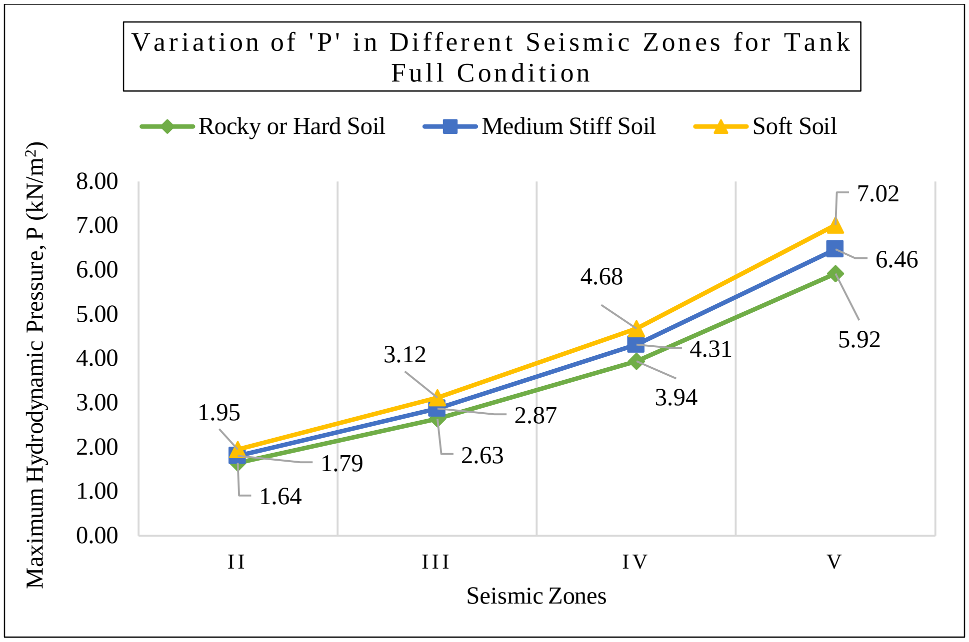


Fig. 19 Variation of 'P' in for tank full condition

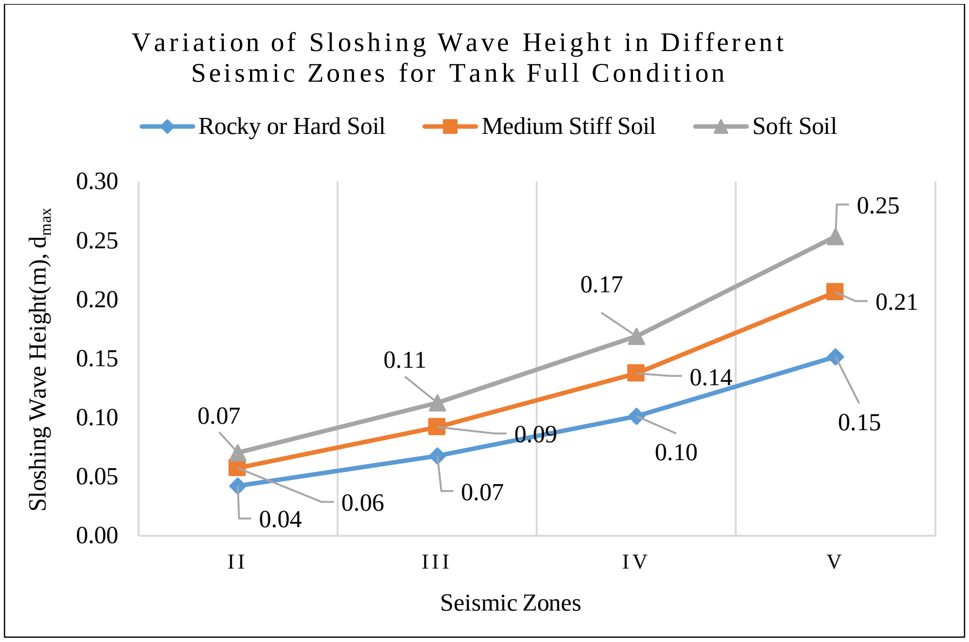


Fig. 20 Variation of sloshing wave height in tank full condition

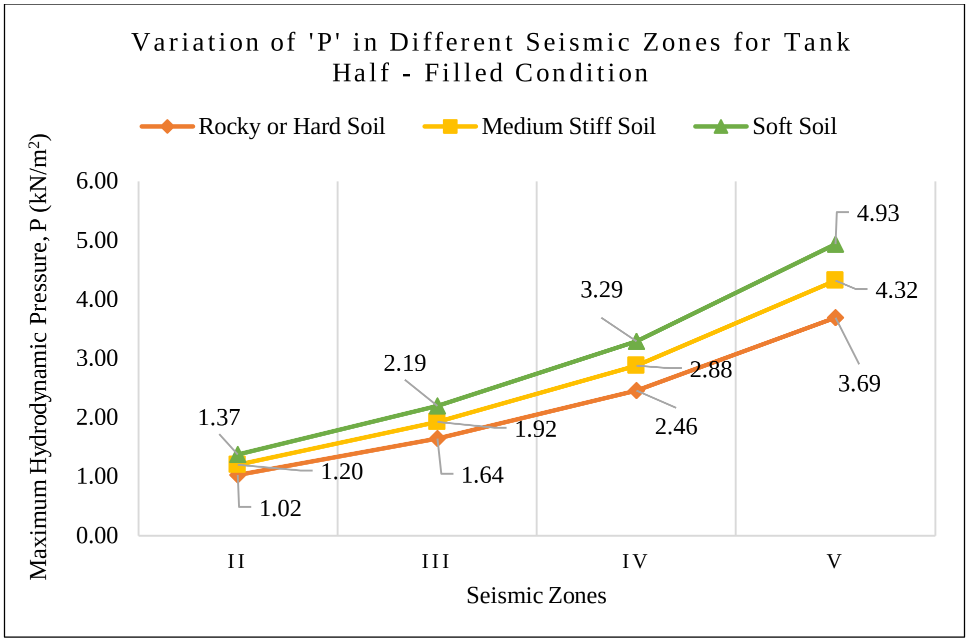


Fig. 21 Variation of "P" in tank half-filled condition

5. Conclusion

This paper presents the estimations of the base shear and moment, impulsive, convective, total hydrodynamic pressure, and sloshing wave height for different water height considerations. The significant outcomes of the study are summarized as follows.

For tank full condition, values of the horizontal seismic coefficient in the convective mode are higher than in the impulsive mode. The values of maximum base shear and overturning moment govern in a tank full condition than those with a half-filled and empty tank. Maximum shear and moment values at base govern in higher seismic zones. Maximum base shear and overturning moment governs in Type-1 soil (rocky hard) condition than with type-2 (medium stiff) and type 3 (soft) soil. The values of the design seismic coefficient in impulsive and convective mode in the lateral direction increase with higher zones [II to V] and are maximum in type 3 (soft) soil. Values of vertical seismic coefficient (Av) increase with higher zones and remain the same for all three types of soil conditions. The values of the maximum hydrodynamic pressure (P) govern the higher seismic zone with a soft soil type.

Values of hydrodynamic maximum pressure (P), hydrodynamic impulsive lateral pressure (Piw), hydrodynamic convective pressure (Pcw) on the base of the wall and wall inertia pressure (Pww) in tank full condition are 30% more in soft soil type, 33% in Medium Stiff Soil and 38% more in Type-1 soil (Rocky or Hard) as compared with tank half-filled condition.

The sloshing wave height governs the higher seismic zone with a soft soil type. The value of the freeboard to be provided should be in accordance with the maximum sloshing wave height. This height shall not be less than the maximum sloshing wave height. Full tank condition governs the maximum hydrodynamic pressure calculations compared with tank half-filled condition. Construction of water tanks on soft soil in higher seismic zones is not desirable.

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