SEISMIC RESPONSE OF BASE ISOLATED LIQUID STORAGE TANKS TO NEAR FAULT PULSE TYPE GROUND MOTIONS

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ABSTRACT:

The seismic response of base isolated liquid storage tanks which are subjected to near fault ground motions are investigated. Tanks with different aspect ratios (liquid heights) and isolation periods are considered. As the ground motion, both real earthquakes and equivalent extracted pulses are used. The sloshing and base shear values of tanks under a series of pulses with different character and pulse periods are also calculated.
Results revealed that, for the preliminary design of tanks in the near fault regions, real earthquakes can be replaced by equivalent velocity pulses especially for isolation periods larger than 3 s.

KEYWORDS: Seismic base isolation, tanks, near fault, velocity pulse

1. INTRODUCTION

Liquid storage tanks are the critical components of industrial facilities. Damage to such structures in earthquakes can result in loss of functionality, fires and environmental pollution. Seismic base isolation is known as a mature innovative method for the vibration control of buildings. It has been widely used in buildings worldwide however its application in industry is limited. There has been numerical studies to investigate the efficiency of seismic isolation in liquid storage tanks. Chalhoub and Kelly (1988) investigated the performance of isolated tanks by various isolation devices. Their results revealed that the total dynamic pressures at the tank wall can be decreased significantly by seismic isolation.
The friction pendulum device is preferred in the seismic isolation of tank as the isolation period is independent of the storage height. Wang (2001) studied the performance of FPS bearings to far field earthquakes. Panchal and Jangid (2008) studied the effects of the near-fault ground motion on the dynamic response of tanks isolated

by FPS bearings. Their results revealed that the real ground motion can be replaced by the single pulse when the isolation period reaches high values.

In this paper, the seismic response of liquid storage tanks base isolated by FPS bearings were calculated. A parametric study has been made to investigate the effects of various parameters such as, tank isolation period, tank aspect ratio and pulse period, on the response of the tank. As the ground motion to the model near field (Northridge-Rinaldi) earthquake records was used. The model was then subjected to the equivalent trigonometric cycloidal pulses extracted from the same events as suggested by Makris (2000). Pulses with different type and character (Type B and Type C) were also considered. Results are presented for comparison with the results from Panchal and Jangid (2008).

2. THE MATHEMATICAL MODEL

The simplified mechanical tank model which was originally suggested by Housner (1963) and Haroun (1983), was used. The model is represented by three effective masses namely convective, impulsive and rigid mass which refer to the liquid sloshing motion, tank wall displacement and the ground motion respectively. Impulsive mass (m_i) and the convective mass (m_c) are considered to be connected to the tank wall by springs having stiffness k_i and k_c and the damping ratios ξ_i and ξ_c, whereas the rigid mass (m_r) has a rigid connection to the wall. Additionally, each of the impulsive and convective masses were analyzed as lumped mass of a single degree of freedom system. It is assumed that the mass of the tank wall is negligible and there is sufficient capacity that the roof does not limit the sloshing liquid. Besides, the liquid is considered not to have rotational displacement, is incompressible and inviscid.

FPS bearings were used as the base isolation system and they are located between the tank ground and the concrete base plate. The horizontal component of the ground motion is considered in the analysis whereas the vertical component was not included. Besides, the overturning effects on the response of the FPS device were found to be negligible in the isolation period range that is studied.

The convective (sloshing), impulsive and rigid masses are expressed by Shrimali and Jangid (2004):

$$m_c = m\gamma_c \tag{1}$$

$$m_i = m\gamma_i \tag{2}$$

$$m_r = m\gamma_r \tag{3}$$

$$m = \pi R^2 H \rho_w \tag{4}$$

And for t_h/r =0.004, the Y_c, Y_i and Y_r ratios are expressed by Shrimali and Jangid (2004):

$$Y_c = 1.01327 - 0.87578S + 0.35708S^2 - 0.06692S^3 + 0.00439S^4 \tag{5}$$

$$Y_c = -0.15467 + 1.21716S - 0.62839S^2 + 0.14434S^3 - 0.0125S^4 \tag{6}$$

$$Y_c = -0.01599 + 0.86356S - 0.30941S^2 + 0.04083S^3 \tag{7}$$

Where, ρ_w is the mass density of the tank liquid; Y_c, Y_i, Y_r are the mass ratios; S= H/R is the aspect ratio of the tank; H is the height of the tank liquid; R is the radius of the tank.

The fundamental frequency of the impulsive mass (w_i) and the sloshing mass (w_c) can be calculated as:

$$\omega_i = \frac{P}{H}\sqrt{\frac{E}{\rho_s}} \tag{8}$$

$$\omega_c = \sqrt{1.84\left(\frac{g}{R}\right)\tanh\left(1.84S\right)} \tag{9}$$

Where, E is the elasticity modulus of the tank; ρ_s is the density of the tank; g is the acceleration of gravity; and P is a dimensionless parameter:

$$P = 0.037085 + 0.084302S - 0.05088S^2 + 0.012523S^3 - 0.0012S^4 \tag{10}$$

The shear stiffness of the impulsive mass (k_i) and the convective mass (k_c) can be calculated as:

$$k_c = m_c\omega_c^2 \tag{11}$$

$$k_i = m_i\omega_i^2 \tag{12}$$

and the damping of the impulsive mass (k_i) and the convective mass (k_c) can be calculated as:

$$c_c = 2\xi_c m_c\omega_c \tag{13}$$

$$c_i = 2\xi_i m_i\omega_i \tag{14}$$

3. THE FPS ISOLATION SYSTEM

The working mechanism of a FPS bearing can be considered as a pendulum. The resisting force (F) produced by the isolator can be expressed as:

$$F = \frac{W}{R}D + \mu W(sgn\ddot{U}) \tag{15}$$

where,
W is the load on the isolator,
D is the horizontal displacement,
μ is the friction coefficient
R is the radius of curvature
U is the vertical ground acceleration (positive when direction is upwards)

and the natural period of the isolator (T_b) can be expressed by Naeim and Kelly (1999):

$$T = 2\pi\sqrt{\frac{R}{g}} \tag{16}$$

4. NUMERICAL ANALYSIS

The 3D-BASIS-ME-MB software program was used to solve the isolated tank model. An example problem which is originally presented by Panchal and Jangid (2008), was studied. The height and the radius of the tank are 11.3m and 6.1 m, respectively. The tank has an elasticity modulus of E=200Gpa, the mass density of the steel is 7900 kg/m^3 and t_h/R is 0.004. The heights of the corresponding convective, impulsive and rigid masses are computed as 11.3m, 6.1m and 3.05m, respectively.
Three different slenderness ratios (1.85, 1 and 0.5) were used to represent the slender, medium and broad tanks, respectively. The natural frequencies of the convective and impulsive masses of the slender and broad tanks were found as 0.27, 1.46, 112 and 6.0 rad/sec, respectively. The damping ratios of the convective (ξ_c) and impulsive (ξ_i) masses of the tanks are 0.5% and 2 % respectively.

Different types of extracted pulses were used to represent the near fault earthquakes (real events) recorded at Rinaldi (Northridge) and Newhall (Northridge) stations. Type A and Type B were used to represent the Rinaldi earthquake and Type C for Newhall earthquake. The model is calibrated by comparing the results from previous researches. Once enough agreement was obtained for the selected ground motions, the analysis was extended to consider the effects of differents pulse types (Type A,B,C) and pulse periods (T_p=0.5 to 6s) for isolation periods varying from T_b=2.0 to 5.0 sec.

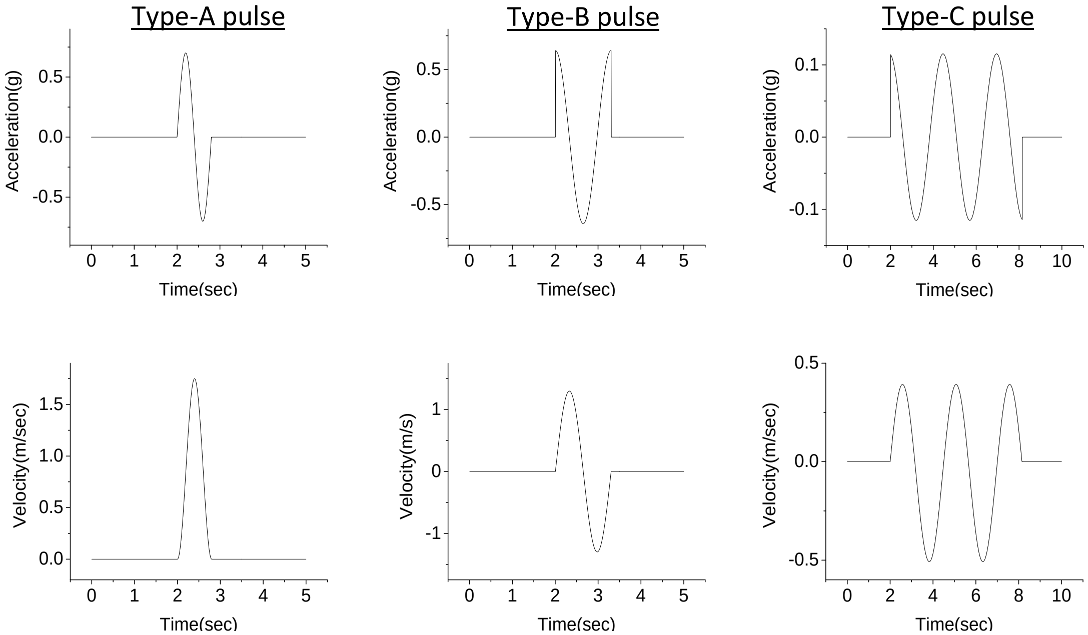
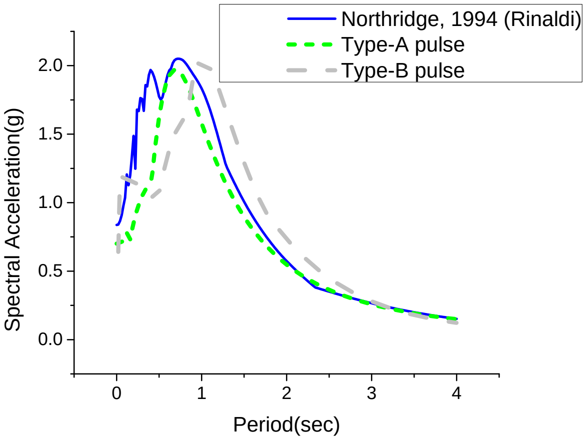


Figure 1.Type A, Type B trigonometric cycloidal acceleration and velocity pulses (T_p=0.8s, 1.3s) characterized complying with the Rinaldi and Type C (T_p=1s) for Newhall earthquakes, respectively

Type A (T_p=0.8s) and Type B (T_p=1.3s) trigonometric cycloidal pulses (acceleration and velocity) were characterized complying with the Rinaldi earthquake data (Makris, 2000) and Type C (T_p=1s) with the Newhall

(Makris, 2000) earthquake as shown in Figure 1. The base shear values (Fb) and sloshing displacements were calculated both for the real earthquake and the equivalent pulses.



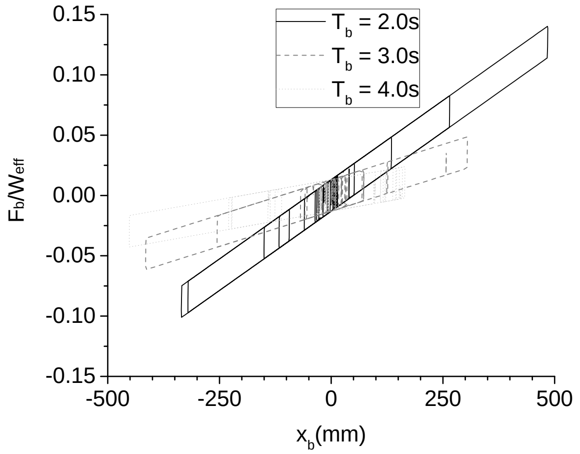


Figure 2. Acceleration spectra for the real earthquake (Rinaldi) and equivalent pulses (Type A – B) and variation of bearing displacement wrt. to the base shear of the slender tanks for Tb=2,3, and 4 s

Figure 3. Bearing force vs. displacement curves for the slender tank isolated by the FPS for isolation periods Tb=2, 3, 4 s under Northridge, 1994 (Rinaldi) earthquake ground motion

The spectral accelerations of the Rinaldi earthquake and equivalent pulses are shown in Fig.2. As can be seen, the spectral values for the real earthquake and equivalent pulses match at a period of 3s.

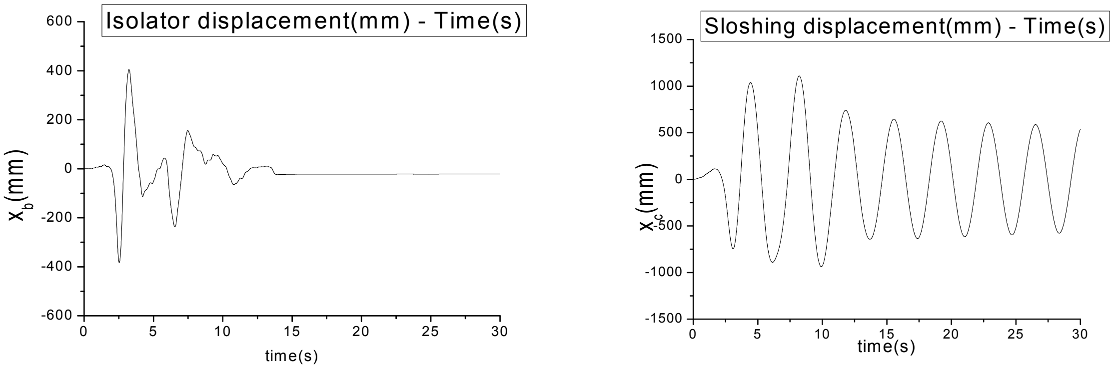


Figure 4. Time variation of base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank isolated with FPS (T_b = 2.5 s and μ= 0.05) under Northridge, 1994 (Rinaldi) earthquake ground motion

Time variations of isolator and sloshing displacements for the slender tank isolated with FPS (T_b = 2.5 s and μ= 0.05) under Northridge, 1994 (Rinaldi) earthquake ground motion are shown in Figure 4.

The variation of base shear values (normalized wrt the effective weight of the tank) of the slender tank (S=1.85) wrt. the isolation period is shown in Fig.5 (left) for comparison with the Panchal and Jangid (2008) (right).

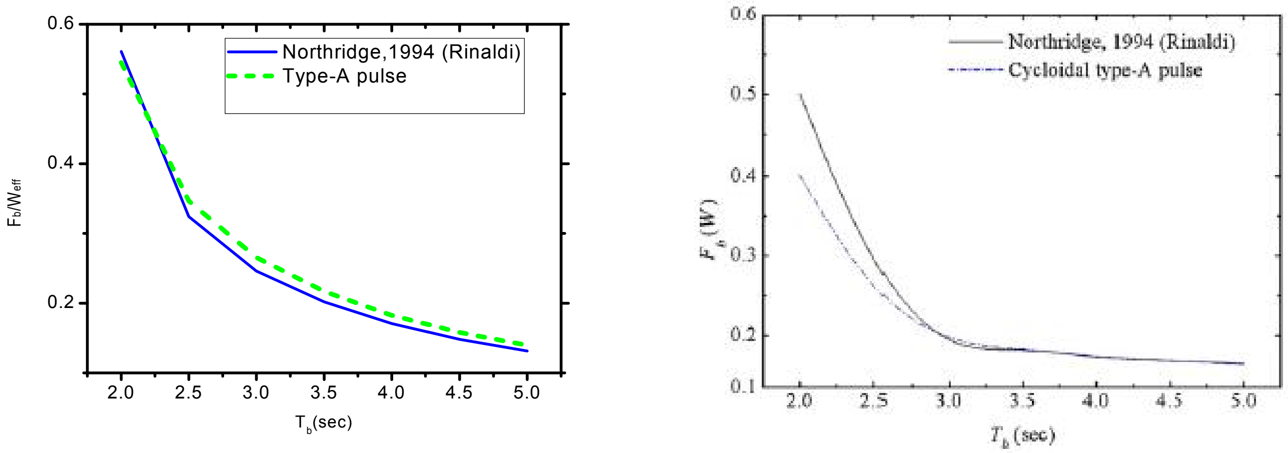


Figure 5. Comparison of variation of peak base shears of slender tank isolated with FPS against isolation period under Northridge Earthquake Rinaldi real data and Type A trigonometric cycloidal pulse (T_p=0.8s)

It is seen that Type A pulse perfectly matches the results of the real earthquake (Rinaldi). The results of the present study is also quite similar to the one provided by Panchal and Jangid (2008) in which a coefficient friction of μ=15% was used for a variable Friction Pendulum System (VFPS). Whereas in the present study, μ=0.05 and single surface FPS was used. The small difference between these two studies are expected to arise from such difference in the data.

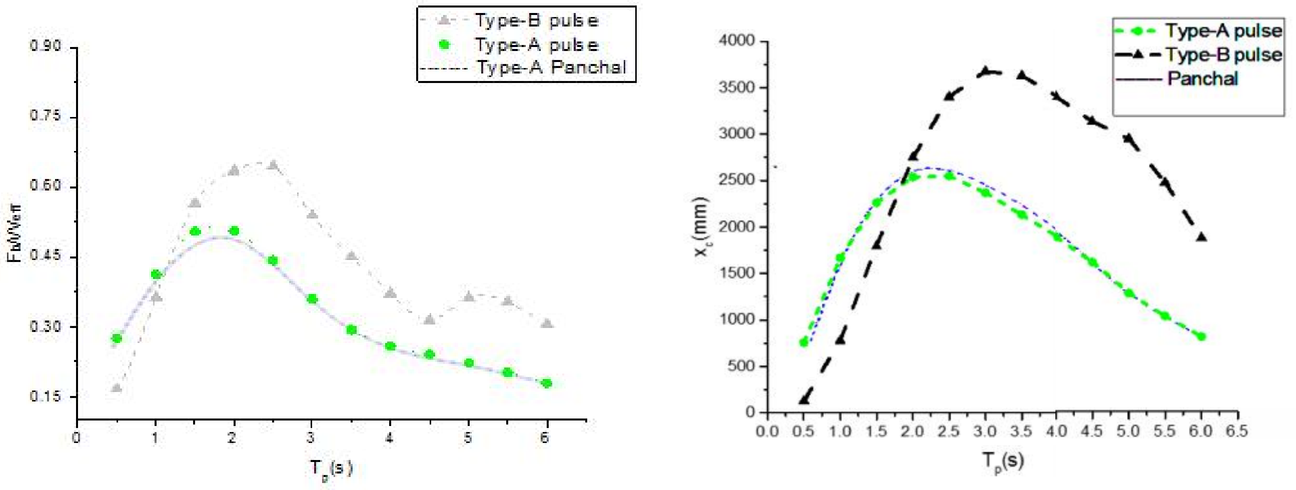


Figure 6. Variation of peak base shear and sloshing displacement of slender tank isolated with FPS (Tb=2.5s) against pulse period under Rinaldi Type A and Type-B pulse data and comparison of the Type A pulse data results with the results of Panchal and Jangid (2008)

Comparison of the results for base shear and sloshing displacements from the present study and Panchal (2008) are shown in Fig.6. It is seen that both results are nearly identical for the Type A pulse indicating perfect agreement between both models. The results for Type B are also represented in the same figure which is quite different from those of Type A. As the results are verified by J Panchal and Jangid (2008) the study is extended to consider Type B and C cycloid pulses as given in Figure 6.

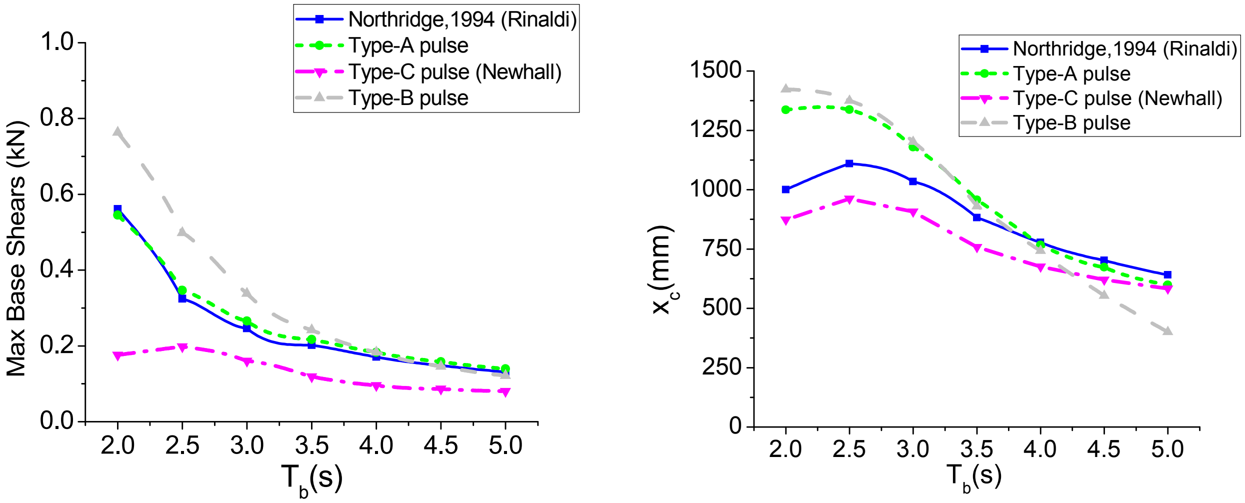


Figure 7. Variation of peak base shear and sloshing displacement of slender tank isolated with FPS against isolation period under earthquake Rinaldi real data, Type A, Type B and Type C (Newhall) pulses

The variation of base shear values and sloshing displacements wrt the T_b for the slender tank is given in Fig 7. As can be seen from the figure base shears decrease wrt to the isolation period, indicating efficiency in the isolation system for all types of ground motions. The efficiency is even more pronounced in the Rinaldi earthquake. It is also seen that the sloshing displacement also decrease wrt the T_b but within a lower rate as compared to the base shear.

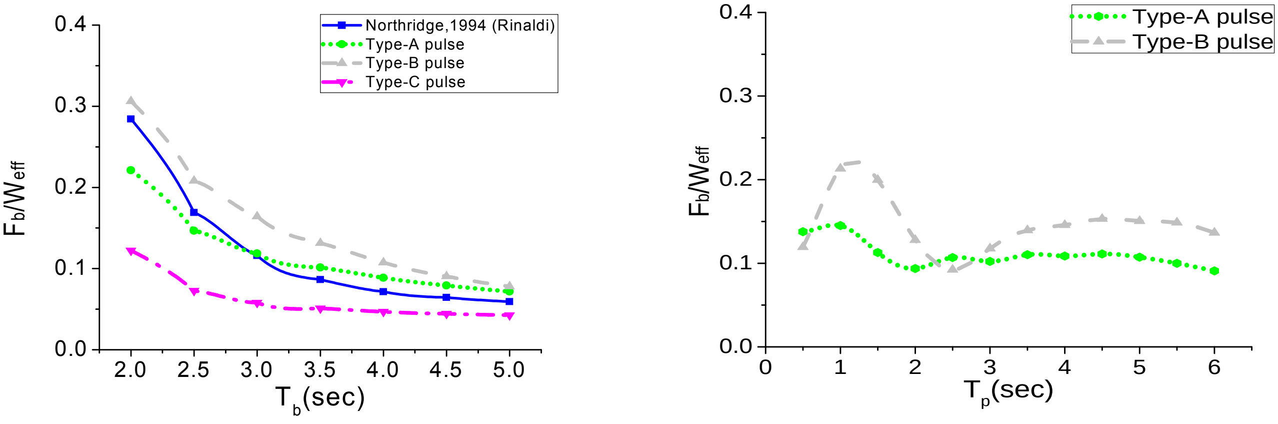


Figure 8. The variation of peak base shear of broad tank (S=0.5) wrt isolation period (T_b) and pulse period (T_p) for (T_b=2.5s) under Rinaldi earthquake (real data), Type A, Type B and Type C (Newhall) trigonometric cycloidal pulses

The variation of base shear values of the broad tank for different values of isolation period and pulse period is shown in Fig 8. As can be seen from the figure base shears decrease wrt to the T_b period, indicating efficiency in the isolation system for all types of ground motions. It is seen that the base shear values are nearly insensitive to pulse periods especially greater than 2.5 s and 3.5 s for Type A and Type B pulses, respectively.

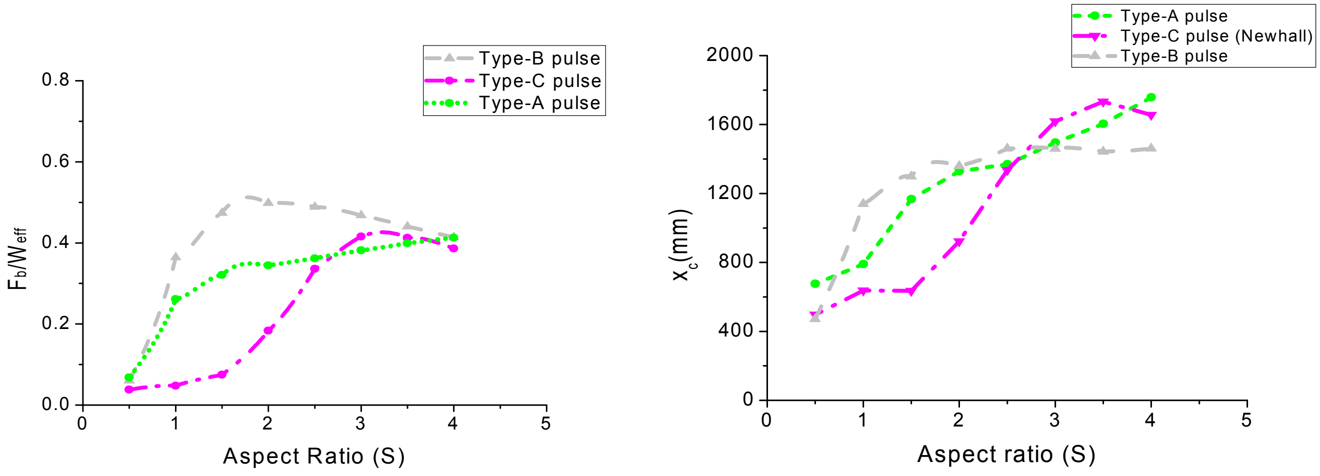


Figure 9. Variation of peak base shear and sloshing displacement of tanks with varying aspect ratios isolated with FPS (Tb=2.5s) under Rinaldi Type A, Type B and Newhall Type C pulse data

The variation of base shears and sloshing displacements for different values of “S” is shown in Fig 9. As can be seen from the figures the base shear values and sloshing displacements tend to increase wrt the “S” and reach to a maximum value at different aspect ratios for every pulse type.

6. SUMMARY AND CONCLUSION

The seismic response of base isolated liquid storage tankssubjected to near fault ground motions was studied. Tanks with different aspect rations (Slender, medium and broad) subjected to (recorded) near fault ground motion with pulse type character are considered. The model was verified by comparing the results with previous researchers for a given tank model under Rinaldi earthquake and pulse (Type A) dor a given isolation period. The analysis was then extended to consider the effects of other earthqukes and pulse types, (Type B and Type C) pulse periosd and isolation periods.

The main outcomes of the present study can be summarized as follows:

- The base shear and sloshing displacements provided from present study and Panchal (2008) are nearly identical indicating perfect agreement between both models

- The base shear values for both slender and broad tanks decrease wrt the isolation period, indicating effectiveness of the isolation system for all cases.

- Optimum isolation period value in terms of base shear values (F_b) was obtained.

- The base shear response is independent of the pulse period (T_p) for, in level of pulse periods.

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The study revealed that, near fault ground motion effect can be simplified as trigonometric cyclic pulse types when the isolation period is about 3s or higher. It is remarkable to decide on the optimum isolation period in the seismic design of tanks which might be useful in the preliminary design of tanks.

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