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LATERAL TORSIONAL COUPLING IN ELEVATED WATER TANK ON HILLY SLOPE

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Abstract

The vulnerability of elevated tank has been shown in past earthquakes, e.g. the 1983 Killari, India earthquake. Further, such structures may become more vulnerable when constructed on a slopy ground of a hilly region as observed in north eastern part of India. This happens because the columns of the staging of such tanks will have unequal length if constructed on slopy ground. This will lead to irregular distribution of strength and stiffness in the staging while mass distribution in container along with water will primarily be of axisymmetric nature. Hence, this structural system will behave as a stiffness eccentric system because of eccentricity between centre of mass (CM) and centre of stiffness (CS). Many a time, this aspect is normally not visualized. Most of the studies are carried out on the elevated tank on flat surface but very little work has been done for the elevated tank standing on hilly slope. This paper is a limited attempt to address the issue. The response of water tank shows a considerable increase as compared to its regular counterpart on flat surface. This apparent increase in the response of structure is due to the considerable eccentricity between center of mass and center of stiffness introducing lateral-torsional coupling which make the structure more vulnerable. The overall outcome shows that during the earthquake the lateral torsionally coupled behavior occurred in the elevated tank structure constructed on slopy ground of hilly region may make it more vulnerable as compared to ones constructed on plane land. Both staging columns and beams are found to develop manyfold increase in induced force quantities.

Keywords: Elevated water tank; Hilly slope; Stiffness eccentricity; Lateral torsional coupling.

1. Introduction

Elevated water tank is a means for supplying water to an entire locality in many developing countries like India, Maxico etc. Such a structure is specially vulnerable to earthquake as such structures have heavy mass supported by a relatively slender staging. Many such structures have failed during past earthquakes (e.g. Killari earthquake of September 1993 [1], Bhuj earthquake of 2001 [2], Chile earthquake of 1960 [3]). The situation may be worse if such structures are constructed on slopy ground of hilly region. In fact such examples are available in various hilly regions of India. For the component of ground motion transverse to the direction of slope, such structures will behave as asymmetric structure with stiffness eccentricity as may be well understood from Fig. 1. Fig. 1 shows because of standing on a slopy ground, columns standing on upward direction of slope are shorter and stiffer than the ones standing on downward direction of slope. Such arrangement introduces stiffness eccentricity moving stiffness centre towards the stiffer columns.

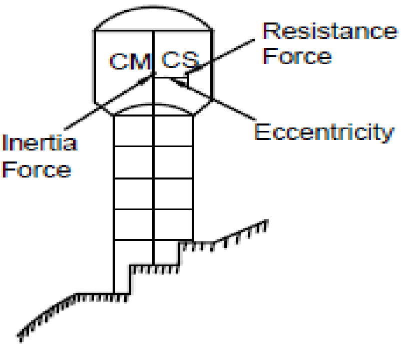
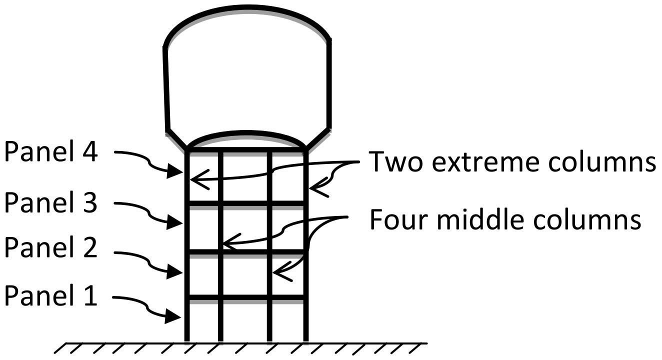


Fig. 1- Elevated tank on slopy ground

In fact, behaviors of asymmetric structures under seismic excitation have been well studied. An extensive list of such studies is available in the literature [4]. However, such studies on elevated water tank are extremely torse on elevated water tanks excepts a few studies considering accidental eccentricity [5].

2. Method of Analysis

To develop a complete insight into the seismic behavior, the study has been carried out in two phases. An elevated water tank with six columns (as shown in Fig. 2) is chosen for the study as this type of elevated water tank is found very frequently all over India.



Details of model of elevated water tank

Capacity of tank	500 m^3
Depth of tank	5 m
Diameter of tank container	11 m
Thickness of wall of tank container	0.25m
Staging Diameter	9m
No of column	6
No of panel	4
Height of staging	4×4 = 16m
Diameter of column	0.6m
Dimension of beam	0.35m × 0.6m
Length of beam	4.5m
Grade of steel, concrete	Fe-415, M30

Fig. 2 - Six column elevated water tank

Initially the behavior has been studied under static lateral load to develop a physical insight. In the next phase of the study, the response of the structure is analyzed due to two well-known ground motions the details of which are shown in Table 1. The ground motions and their response spectra are shown in Fig 3. The elevated water tank is modeled in standard finite element software.

Table 1- Details of ground motion

Record no.	**Year**	**Earthquake**	**Station**	**PGA (g)**	**Duration (in second)**
1	1992	Big Bear	Desert Hot Spr.(New Fire Stn.)	0.23	60
2	1979	Imperial-Valley	Calexico	0.27	193.9

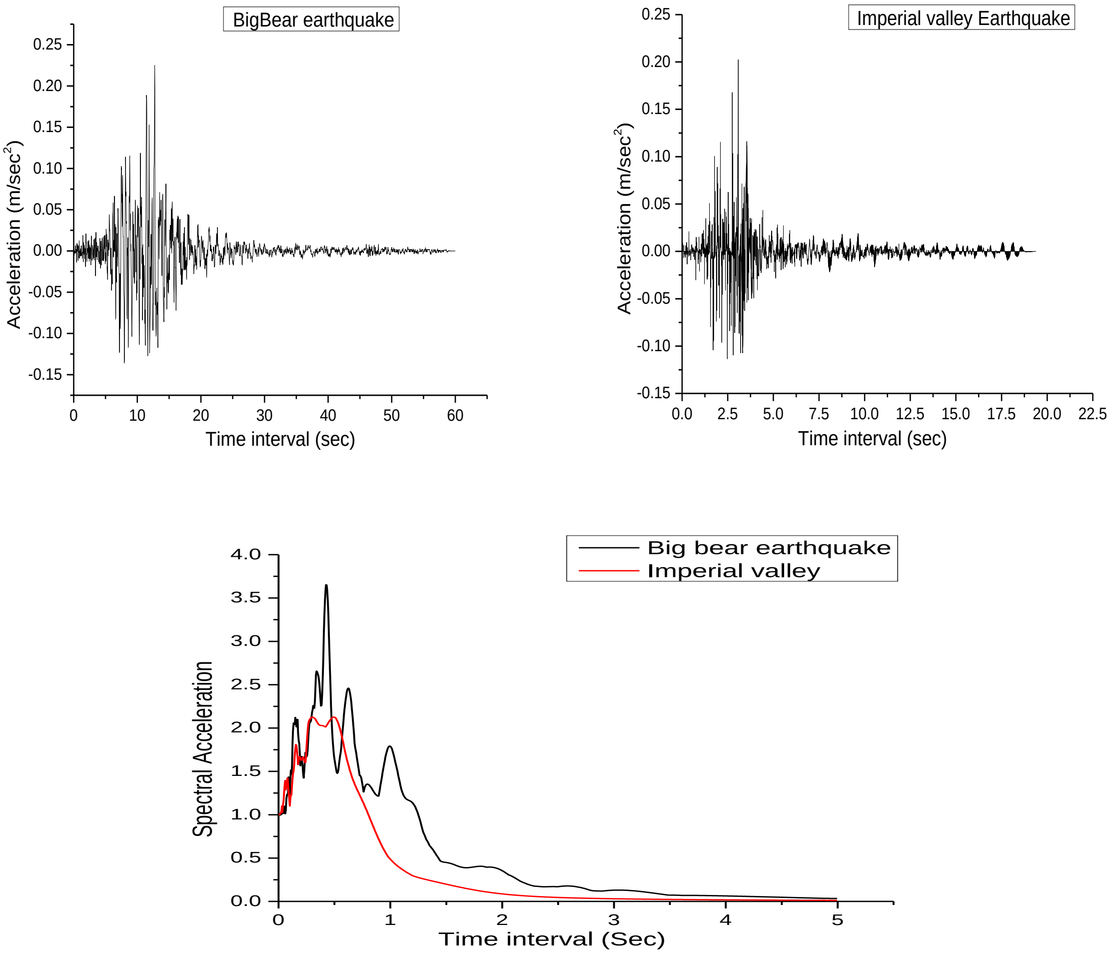


Fig. 3 - Seismic ground motions and their response spectra

To represent the rigid behavior of tank container, rigid members are used at staging top and a vertical rigid member from centre of staging top to the centroid of the elevated tank is also attached. At the top of this vertical bar, static lateral load is applied for static analysis while the entire mass of the tank container in tank full condition and 1/3rd mass of the staging is lumped at the same point as per the established guidelines [6] as shown in Fig 4 for seismic analysis.

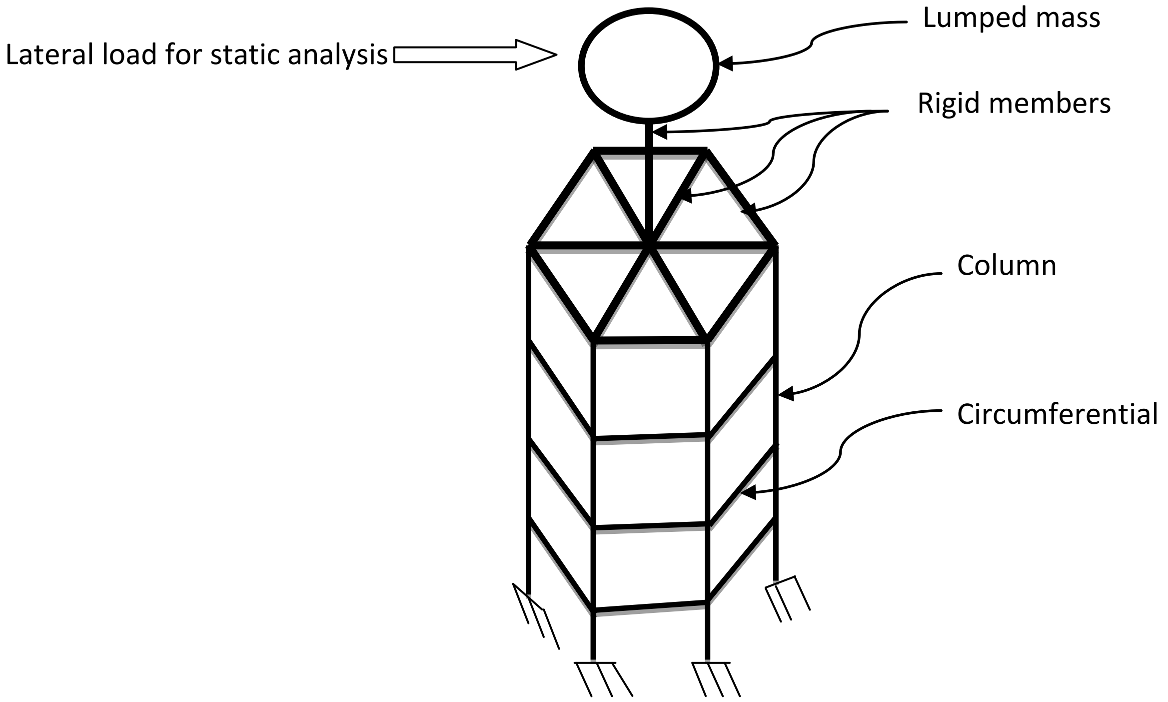


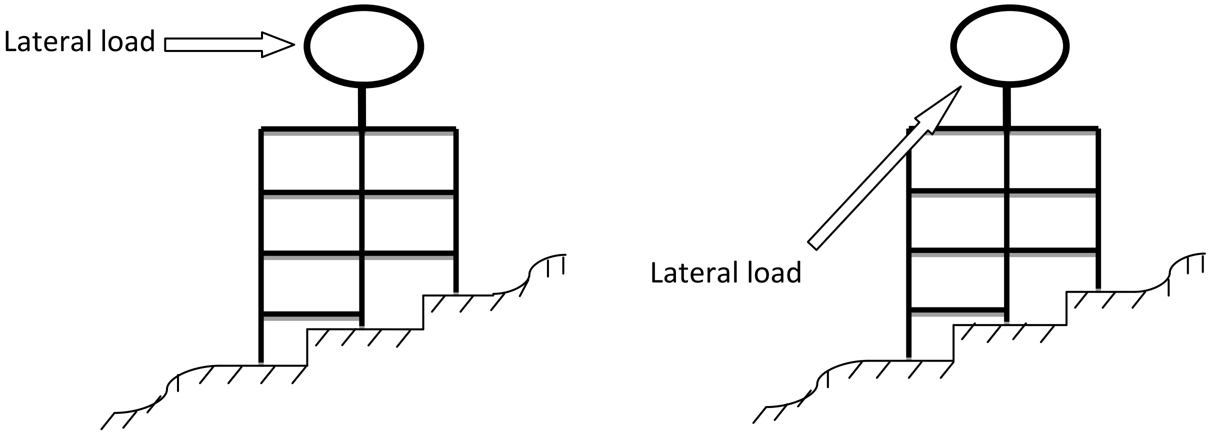
Fig. 4 - Idealized FEM model used

3. Results and Discussion

Results are presented in two subsections. First subsection presents the behavior of the structure under static lateral load while the next subsection presents the response behavior under two seismic ground motions as shown in Fig 3.

3.1 Behavior under static lateral load

Maximum bending moment in column (M_{col}) and maximum bending moment in beam (M_{beam}) are chosen as two design quantities required for ensuring the safety of the supporting staging structure. In fact, once the maximum design moment is obtained, the maximum shear force in members of the staging can be obtained by dividing the maximum bending moment by half of the span as point of inflection in such members occurs nearly at midpoint of the member. Two cases are considered in the first case, the lateral load is applied on the idealized model of the elevated tank structure along the direction of slope while in the second case, the load is applied across the direction of slope as shown in Fig 5.



(a) Load is along the direction of slope. (b) Load is across the direction of slope.

Fig. 5 - Load applied on the idealized model of the elevated tank structure.

The maximum bending moment in column obtained for elevated tank staging standing on the slope for these two cases, are shown in Fig 6, as a function of slope angle θ. The maximum bending moment in columns (M_{col}) of staging on slope is normalized by design bending moment in columns of staging on plane and the normalized bending moment (normalized M_{col}) is plotted in the figures. This exhibits relative values of design quantities for staging on slope as compare to that of staging on plane. Since same lateral force is applied for both the staging, these values are independent of magnitude of lateral force applied.

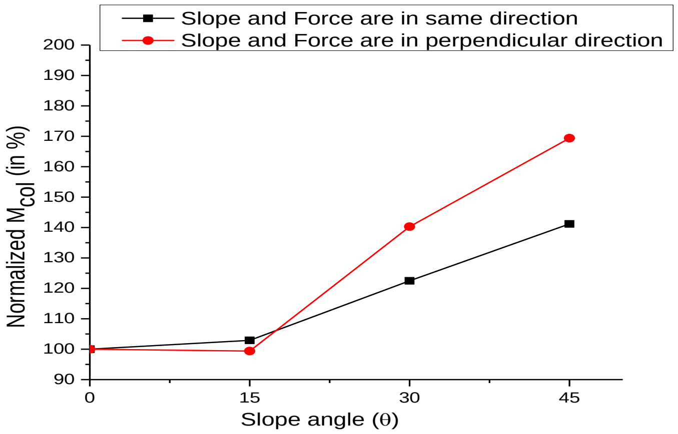
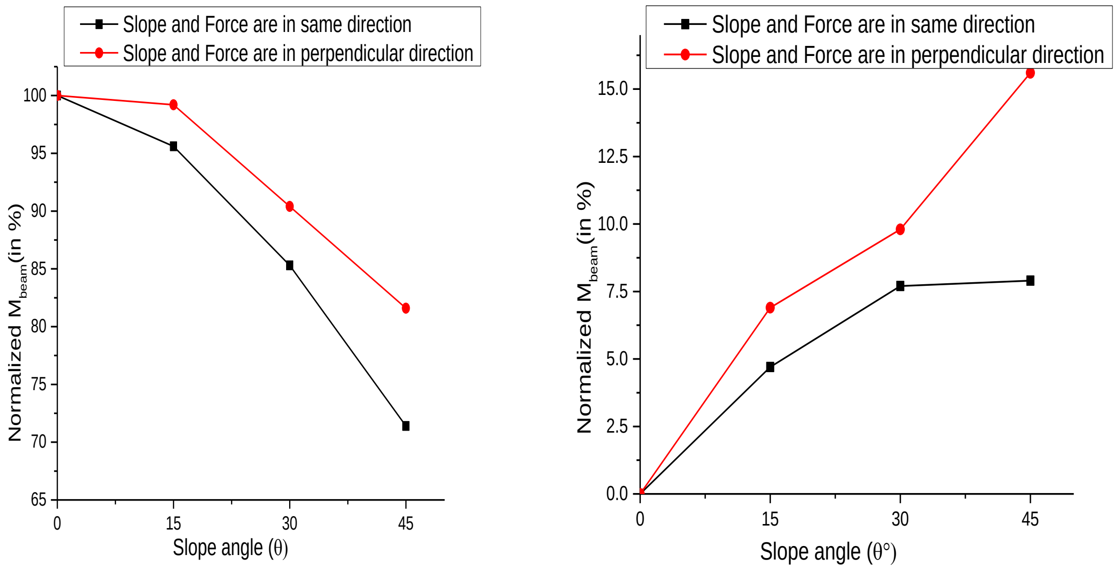


Fig. 6 - Change in normalized bending moment in columns due to the effect of slope.

The figure shows that when the slope angle increases, the increase in bending moment in columns also becomes more. The maximum increase is only about 40% for the first case, i.e. when lateral load is parallel to the direction of slope. On the other hand, the increase in bending moment of columns (normalized M_{col}) for the lateral load acting perpendicular to the slope comes to be about 70%. Such a considerable increase occurs due to development of lateral-torsionally coupled deformation as the structure becomes asymmetric with respect to the direction of lateral force. This indicates that effect of asymmetry cannot be ignored.

Fig. 7 presents increase in maximum beam bending moment of elevated water tank staging on slope normalized with respect to beams of similar staging constructed on plane. This normalized moment is denoted as ‘normalized M_{beam}’. In addition to the occurrence of bending moment in vertical plane passing through the longitudinal axis of the beam, it has also been found that bending moment also develops in horizontal plane passing through the longitudinal axis of the beam. Such bending moment does not occur in case of tanks staging built on the plane ground.



(a) (b)

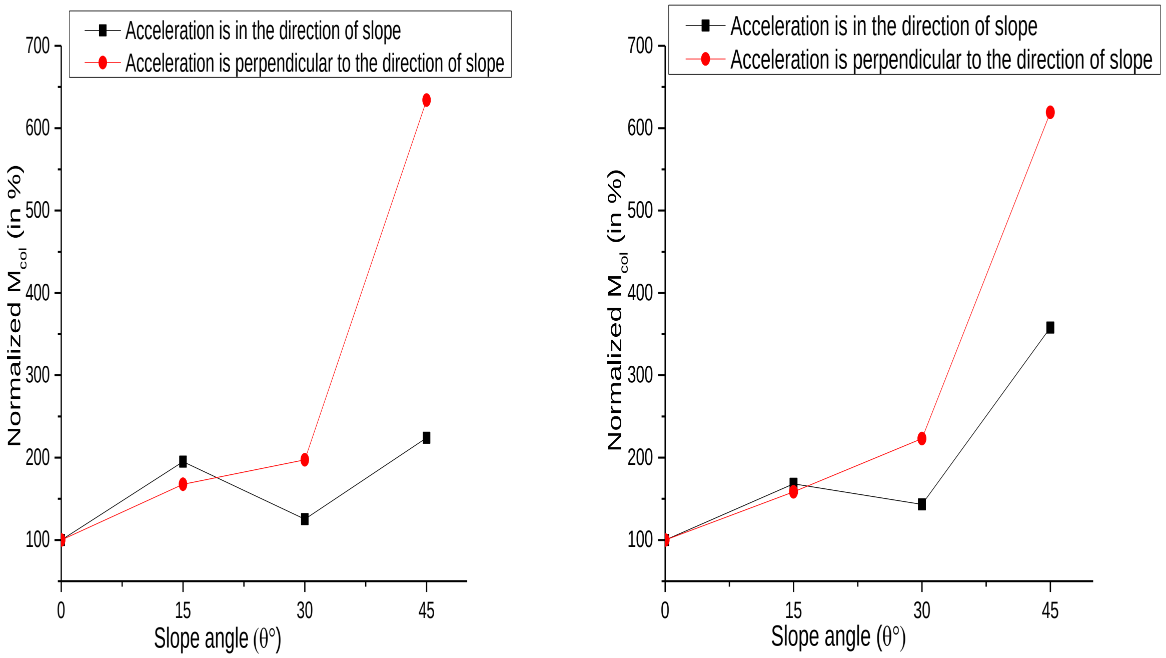
Fig. 7 - Variation of normalized bending moment in beams of tank staging resting on slope as a function of slope angle (θ): (a) Bending moment in vertical plane. (b) Bending moment in horizontal plane.

Fig. 7(a) presents the variations of normalized bending moment in vertical plane along with variation of slope angle θ, while Fig. 7(b) shows the similar variations for bending moment developed in horizontal plane to see the quantitative importance of such bending moment from the view point of design. Fig. 7(a) shows that bending moment in vertical plane is decreasing for staging constructed on slope as compared to its similar counterparts in staging resting on plane. Very appropriately speaking, the beams in staging resting on slope are subjected to biaxial bending and for truly optimum design of such issues should be given due consideration. This points out the need of studying the behavior of such structures under the real seismic excitation as the effect may be more severe because of dynamic amplification and participation of number of modes.

3.2 Behavior under seismic ground motion

For assessing the behavior under the seismic ground motion, lumped mass is provided at the centre of mass of the tank as discussed earlier and shown in Fig. 4. Two well-known ground motions are considered, which are listed in Table 1. These ground motions and their response spectra are shown in Fig. 3. These ground motions are used for both the cases of loading namely parallel to the direction of slope and perpendicular to the direction of slope. Further, linear time history analysis is carried out with the help of step by step integration method. Likewise static analysis, the duration of ground acceleration is along the direction of slope of idealized model of elevated tank structure in first case; while in the second case, the same is considered across the direction of slope.

Maximum bending moment in column (M_{col}) and maximum bending moment in beam (M_{beam}) are considered as two design quantities as considered for static loading. The maximum bending moment in columns obtained for elevated water tank staging standing on the slope for the two cases mentioned above using the above two ground motions are shown in Fig. 8.



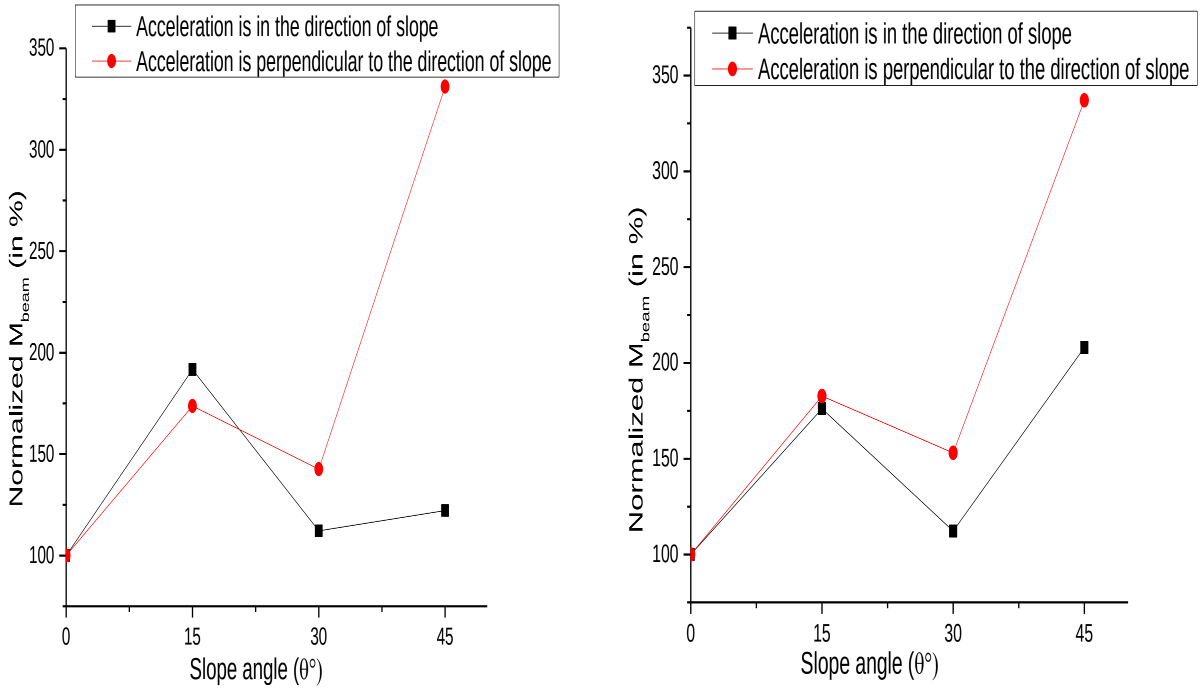
(a) (b)

Fig. 8 - Change in normalized bending moment in column due to the effect of slope: (a). Normalized M_{col} (in %) vs slope angle for Big-bear earthquake ground motion. (b). Normalized M_{col} (in %) vs slope angle for Imperial Valley ground motion.

Fig. 8(a) shows the change in normalized bending moment in columns due the effect of slope due to excitation caused by Big bear earthquake ground motion and in Fig. 8(b) shows the same due to Imperial Valley earthquake ground motion.

Responses for both the ground motions are found approximately similar as may be observed from Fig. 8. The figure shows that with the increase in slope angle, increase in bending moment in columns becomes more. The maximum increase in bending moment of column (normalized M_{col}) for steep slope is about 150% to 250% when excitation direction and direction of slope are parallel. On the other hand, increase in bending moment in columns (normalized M_{col}) for ground motions across the slope i.e. perpendicular to the slope is found to be more than 500%. This drastic change occurs in the second case as the structural system becomes asymmetric with respect to direction of ground slope. In fact, the effect of lateral torsional coupling in the staging of elevated water tank in this case becomes more severe due to dynamic amplification.

Fig. 9 and Fig. 10 show the maximum increase in bending moment of beam of elevated water tank standing on slope normalized with similar counterpart occurring in tank staging constructed on plane. This normalized bending moment is denoted as 'normalized M_{beam}' for maintaining consistency.

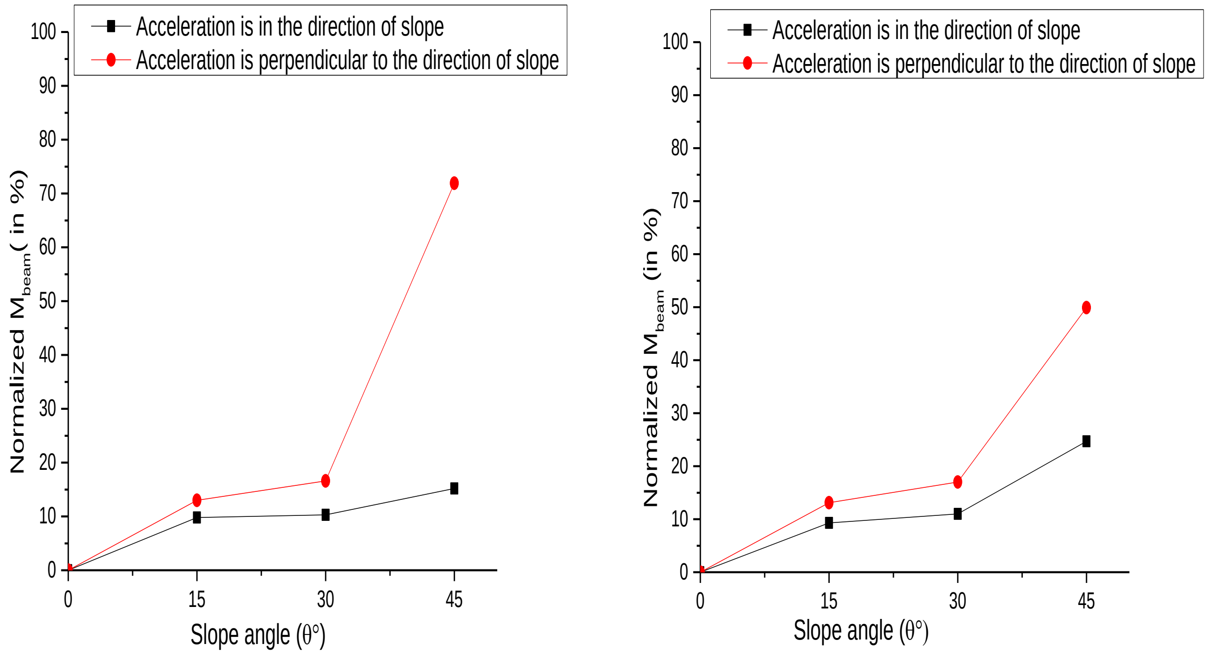


(a) (b)

Fig. 9 - Variation of normalized bending moment in vertical plane for beams of tank staging resting on slope as a function of slope angle (θ): (a) Bending moment in vertical plane for Big-bear earthquake ground motion. (b) Bending moment in vertical plane for Imperial Valley earthquake ground motion.

Fig. 9(a) and 9(b) present the variations of normalized bending moment in vertical plane of staging beam along with the slope variation for Big-bear and Imperial Valley earthquake ground acceleration respectively. From these graphs it can be seen that for the first case i.e. when ground acceleration is parallel to the slope, changes are about 100% to 150%. Again, in the second case, when the ground motion acceleration and slope are perpendicular to each other, changes are about 250% for a steep slope of 45°.

Fig. 10(a) and 10(b) show the similar variation for bending moment developed in horizontal plane as explained in section 3.1. From the figure, it can be seen that when ground motion and slope are along the same direction then this change is not considerable. As this value is about 15% to 25% of bending moment in vertical plane as compared to M_{beam} of staging constructed on plane. But for the later case when ground motion and slope are perpendicular to each other then beam should be designed for biaxial bending. This is suggested because, it can be observed from the results that there is considerable development of bending moment in horizontal plane about 50% to 75% of vertical bending moment of beam in staging of elevated water tank on plane.



(a) (b)

Fig. 10 - Variation of normalized bending moment in horizontal plane for beams of tank staging on slope as a function of slope angle (θ): (a) Bending moment in horizontal plane for Big-bear earthquake ground motion. (b) Bending moment in horizontal plane for Imperial Valley earthquake ground motion.

4. Summary and Conclusions

Elevated water tanks resting on slopy ground are observed in seismic prone north eastern region of India and perhaps in the hilly region of earthquake prone zone of various countries. Such tank structures are found to be distressed in past earthquakes (e.g. [7]). In this context, the present study is an attempt to observe the extent of seismic vulnerability due to irregularity introduced in the supporting staging structure on slope. The study leads to fallowing broad conclusions.

1. The behavior under static lateral load indicates that the effect of increase in column bending moment is observed while a slight decrease in beam bending moment occurs when force is in the direction parallel to slope. When load is applied perpendicular to the direction of slope, making the staging asymmetric with respect to the direction of slope, because of torsional deformation maximum column bending moment exceeds about 70% with respect to the same in column of the staging resting on plane.
2. The beam of staging on slope shows a slightly decreasing trend in bending moment as compared to its counterpart in staging on plane land. However, they are subjected to biaxial bending because of development of bending moment in horizontal plane passing through the longitudinal axis of the beam in addition to expected bending moment in vertical plane.
3. The dynamic behavior of such structure shows the similar trend, however, in much more amplified form. For instance the maximum column moment in staging on slope may shoot up to an increase of 500% as compared to the same occurring in staging on plane.

4. Similarly the bending moment in staging beams exhibits about 250% increase as compared to the same in staging on plane. Further the beam of staging on plane exhibits biaxial nature of bending, which is unusual. Hence, they should be design accordingly.

This preliminary study indicates that elevated tank resting on slope may exhibit considerable additional vulnerability as compared to the elevated tank staging standing on plane. Hence, a detailed study under a large number of ground motions is needed to be carried out to arrive at acceptable design guideline in this regard. Such future study may consider the effect of impulsive and convective mass of water respectively for making the idealized structure model more realistic. Inelastic behavior should also be included in such further study to have more definitive idea about the seismic behavior of such structures. Such studies are in progress and will be reported as and when completed.

5. Acknowledgements

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6. Copyrights

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