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Effect of the Geometric Shapes of Elevated Tanks on their Dynamic Response

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Abstract—**This study examines the impacts of geometric shapes of elevated tanks owing to the seismic loading action. Four typical tank shapes have been studied, namely: intze tank with a shaft, pure conical tank with a frame, combined conical tank, and cylindrical tank with a frame through a single degree of freedom, two degrees of freedom, and three dimensional finite element method, based on the full and empty condition using computer simulation program LUSAS FEA through added mass approach for accounting fluid-structure interaction. The results revealed that the intze shape is the most suitable shape to be analyzed based on mechanical approaches. While the impossibility of applying these approaches to conical tanks.**

Index Terms: **seismic response, elevated tank, codal provisions, impulsive mass, convective mass.**

I. INTRODUCTION

The presence of liquid in an elevated tank and its concentration of their masses with upper parts of the tank excreted hydrodynamic pressure on the walls of the tank as a result of earthquake loads, giving effects considered by the increase in base shear and overturning moments.

In the late 1950s and early 1960s, the seismic force design of tanks was based on a single lateral force coefficient applied to the tank as a rigid body in a manner similar to that used in the design of a one-story structure namely single degree of freedom idealization (SDOF). By the mid to late 1960s, it was recognized that the fluid motion in the tank could contribute significantly to its response [1] and later the idealization of elevated tanks had become based on two degree of freedom (two-DOF). Analyzing the elevated tanks through mechanical approaches (SDOF and two-DOF) still adopted in most seismic codes such as Eurodode-8 [2], ACI-371R-8 [3] and NZSEE [4]. Although over the last few decades, the rapid development of computer hardware and finite element method (FEM) software for which the capability of implement the FEM model become more realistic to prescribing the real dynamic behavior of elevated tanks, and a wide variety of shapes of elevated tanks for different purposes. It has become a must to check the applicability of utilization the mechanical models according to their shapes. Geometry and uniformly distributed mass and stiffness of such structures have a great influence in safety and economy.

Over the years, many analytical models based on codal provisions and FEM have been developed by researchers to advance the state of knowledge to its seismic behavior. However, there are still some aspects that require further investigation according to their shapes. Durgesh and Bhumika [5] developed eight models with different shapes to estimate the seismic response of real storage tanks affected by Bhuj earthquake, based only on existing code design procedures, including soil-structure-fluid interactions (FSI and SSI), but the accuracy of results could lack the needed FEM models to justify findings. Livaoglua [6] dealt with SDOF, Two-DOF and compared their results with 3D FEM of one shape of an intze elevated tank and obtained reasonable results. Nandagopan and Shajee [7] study four elevated tank shapes, two ground (circular and rectangular) and two elevated (circular and rectangular), based on mechanical approaches and FEM and compared the reactions with also at varying water levels, their results show a difference between the two approaches of less than 7%. Nakul Gupta [8] study the impacts of hydrodynamic forces on intze elevated tanks with different system staging (framed and shaft) and different seismic zones with respect of also just codal provisions.

The irregular shapes of tanks in previous studies such as conical shapes have not been considered widely, probably the present impediments to progress toward improving the seismic safety evaluation procedures for the elevated tanks. For a better understanding of seismic behavior of tanks, the main objective of this study is to investigate the seismic behavior of various shapes of elevated tanks, and check the applicability of utilizing mechanical approaches procedures compared to the FEM with considering of FSI effects.

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II. MODELLING STEPS

The understanding of modeling steps, starts from SDOF to Two-DOF in which is easier to implement according to seismic codes regulations than FEM models. Modeling steps through FEM needs a thorough understanding of FEM as a numerical method. In this study, Euro Code part 8 (EC-8) [2] provisions for the implementation of codal models and LUSAS FEA software were adopted to perform analysis through free vibration, furthermore, damping ratio is assumed to be 5.0% (Type 1) for the concrete structures and 0.5% (Type 2) for the sloshing motion. Figure 1 shows the models (mechanical and FEM) development process as a flowchart diagram.

Due to lacking of data for microzoning studies in study area (AL-jufrah Libya), the design of ground acceleration is taken to be 0.19 g. So, it is assumed that elevated tanks are built in a moderate seismicity zone, and the parameters of response spectrum used in this study presented in Table 1.

Table 1. Parameters of response spectrum according EC-8

Parameters	Value
Design ground acceleration on type A ground (ag)	0.18
Lower bound factor (β)	0.2
Behavior factor (q)	2.5
Correction factor (λ)	1.0

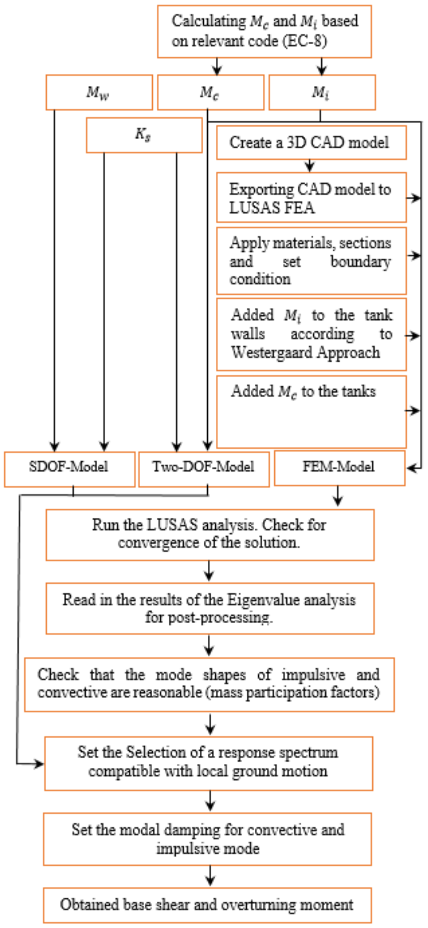
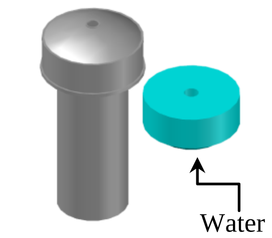
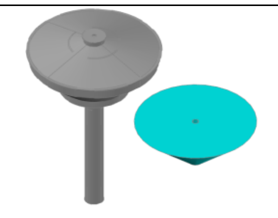
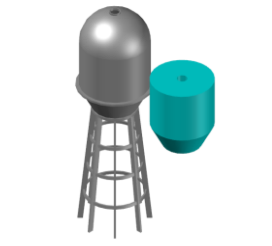


Figure 1. Modelling steps

A. Tanks Description

Four typical elevated tanks were chosen with different volume capacities and shapes. For each one, two different filling conditions were considered (full and empty). A structural model using the generalized SDOF and Two-DOF, obtained using the current practice code and FEM. Schematic diagrams showing the various component volumes of the tanks are in Table 2.

Table 2. Volume of staging, containers and water of elevated tanks

Volume (m^3)		Vs	Vc	Vw
Intze tank with shaft (Tank-1)		213.19	113.21	906.94
Pure conical tank with frame (Tank-2)		77.42	216.33	1018.91
Combined conical tank with shaft (Tank-3)		387.82	2157.53	8824.62
Cylindrical tank with frame (Tank-4)		56.35	177.75	707.59

V_s volume of staging, V_c volume of container and V_w volume of water.

B. Idealization Based on Codal Provisions

In the case of idealization as an equivalent SDOF system and the tanks are in empty condition (Table 3). Two parameters are needed to be defined: mass m_1 which is consisted of the mass of the tank + 1/3 mass of the staging frame and K_s is the lateral stiffness of the staging, which can be numerically or analytically obtained, in this study is obtained numerically through FEM (LUSAS FEA) using beam element (BMS3), while rigid links are assigned to BMS3 element from the top of staging to the center of gravity (CG). By applying an arbitrary force (F) at CG and obtaining a corresponding draft (Δ) as shown in Figure 2, K_s can be calculated through the equation below.

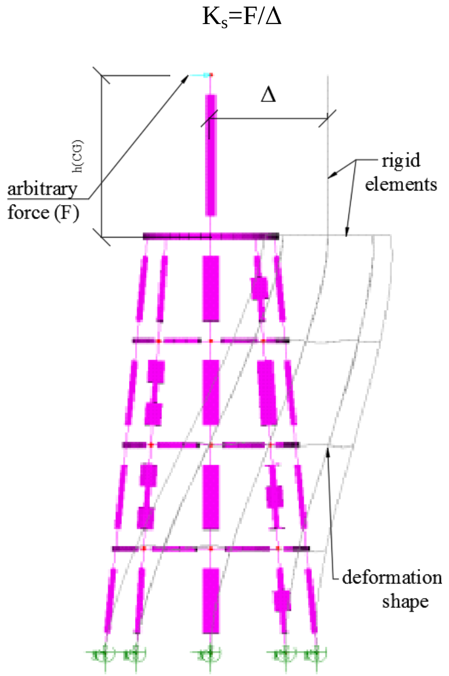
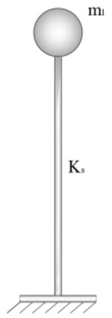


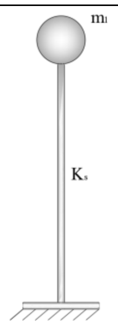
Figure 2. Obtaining the stiffness of staging (Tank-4)

Table 3. Idealization of the empty elevated tanks based on SDOF

	Tank type	m_l (Kg)	K_s (kN/m)
	Tank-1	4.70E5	937.74E3
	Tank-2	6.17E5	23.90E3
	Tank-3	58.27E5	167.19E3
	Tank-4	5.01E5	14.47E3

While. if the tanks are full, mass m_l consisted of a mass of water + mass of tank + 1/3 mass of staging frame and Ks is same as a full case (Table-4)

Table 4. Idealization of the full elevated tanks based on SDOF

	Tank type	m_l (Kg)	K_s (kN/m)
	Tank-1	10.80E5	937.74E3
	Tank-2	16.36E5	23.90E3
	Tank-3	146.52E5	167.19E3
	Tank-4	12.08E5	14.47E3

The seismic response of elevated tanks depends on complex FSI that may result in global overturning moments and base shear induced by horizontal inertial forces. Hence the seismic behavior of tanks subjected to the earthquake are characterized by two predominant modes of vibration, the first mode is that of sloshing mass of the liquid (convective mass) m_c, the second mode is that of the combined structure and non-sloshing mass of liquid (impulsive mass) m_i as shown in Figure 3, initially developed by Housner [9] and this simplified procedure of FSI is also adopted and promulgated by most seismic codes [2-4] and researchers [10-13], Table 5 presented the dynamic parameters determinates based on EC-8.

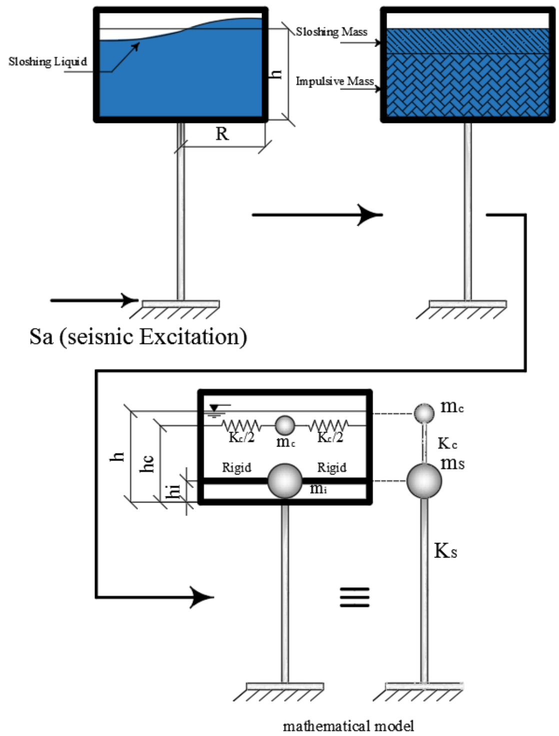
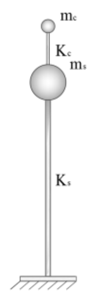


Figure 3. Characterized impulsive and convective masses

Table 5. Idealization of the full elevated tanks based on two-DOF

	Tank type	m_s (Kg)	m_c (Kg)	K_s (kN/m)	K_c (kN/m)
	Tank-1	10.80E5	3.06E5	937.74E3	0.82E3
	Tank-2	16.36E5	10.80E5	23.90E3	1.09E3
	Tank-3	146.52E5	10.80E5	167.19E3	2.52E3
	Tank-4	12.08E5	10.80E5	14.47E3	0.65E3

in which m_s consists of a convective mass (m_i) + mass of tank + 1/3 mass of staging frame and K_s is same as SDOF, K_c is spring stiffness of convective mode.

C. *FEM Models*

FEM models provide advanced possibilities in a simulation of tanks and the ability to deal with a variety of constitutive models. This causes the solution to be more accurate than traditional codal techniques.

Table 6 and Figure 4 presented the elements used to build the models and their properties, furthermore the grade of concrete M20 and density of concrete 25kN/m^3. Added mass approach is adopted for FSI considerations, m_i added to the wall tanks based on Westergaard method (hydrodynamic pressure) [14] and m_c connected with tank wall by spring link with stiffness K_c, all beams and columns are simulated as a thick beam, whilst SSI effects are ignored and idealized supports with a fully fixed boundary condition. different adaptive mesh refinement configurations were tested to ensure if a mesh is fine enough for accurate results.

Table 6. Describes of elements used to build the models [8]

Element name and their symbol	Utilizing to simulate:	Degree of freedom /node
thick beam element (BMS3)	columns and beams	6
quadrilateral thin shell (QSI4)	Walls, domes, slabs and shafts	6
non-structural mass (PM3)	convective and impulsive masses	3
joint no rotational stuffiness (JNT4)	link between convective mass and tank wall	3

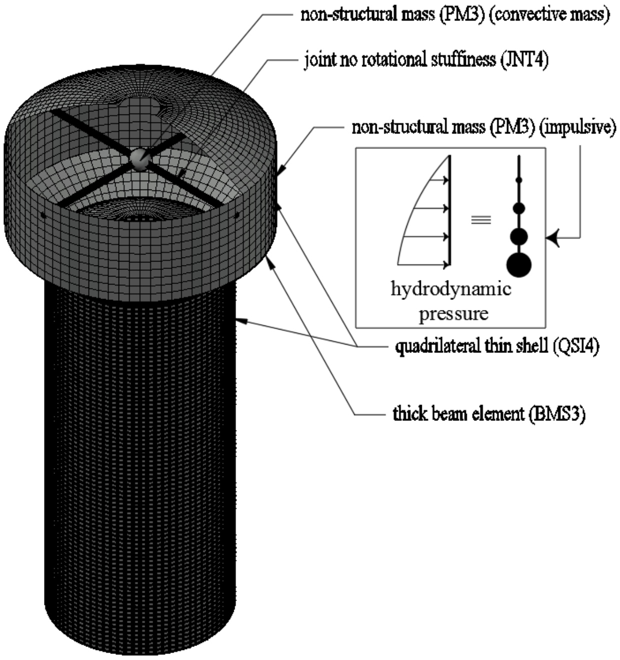
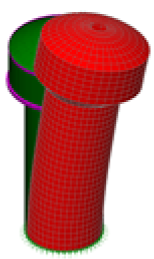
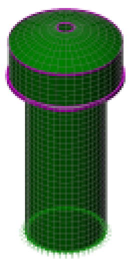
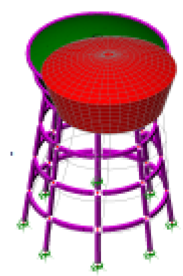
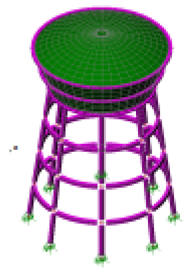
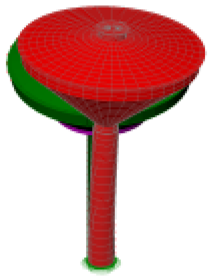
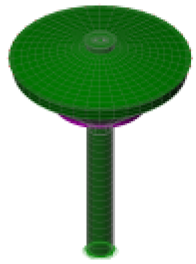
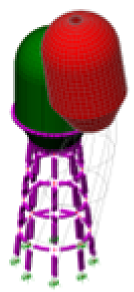


Figure 4. Accounting FSI effects

The 3D-FE mesh of the full models is presented in Table 7 within a FE package associated with impulsive mode shape for all tanks.

Table 7: FEM models and impulsive mode shapes of elevated tanks

Impulsive mode shape	FEM Model	
		Tank-1
		Tank-2
		Tank-3
		Tank-4

III. RESULTS AND DISCUSSION

Generally, from all of the cases presented in Figure 5 periods for convective mode (T_c) obtained for four models of tanks in which FSI effects is takes into account a marginal difference is observed in the values of T_c according to Two-DOF and FEM for Tank-1 where the percentage difference is 0.24% in which the results of this study was consistent with previous studies [6, 15] whilst for Tank-2, Tank-3 and Tank-4 are 10.00%, 8.51%, and 9.77% respectively in which are relatively overestimated due to more severe mass irregularity. which is strongly indicates that, as the tank is more conically shaped as the variation of Tc becomes more.

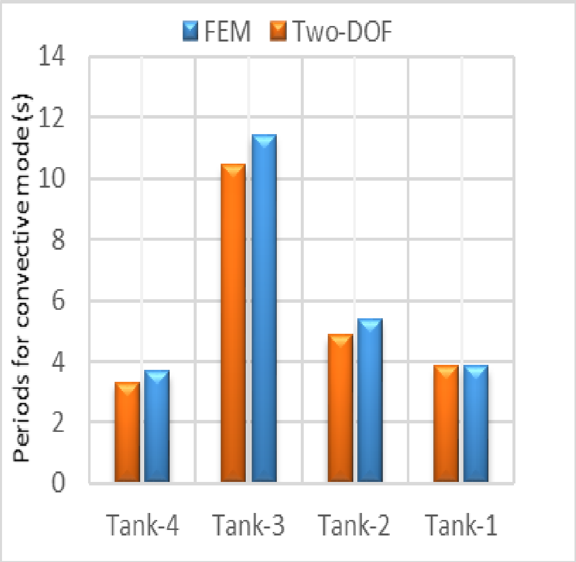


Figure 5. Periods for convective mode obtained for four models (Full)

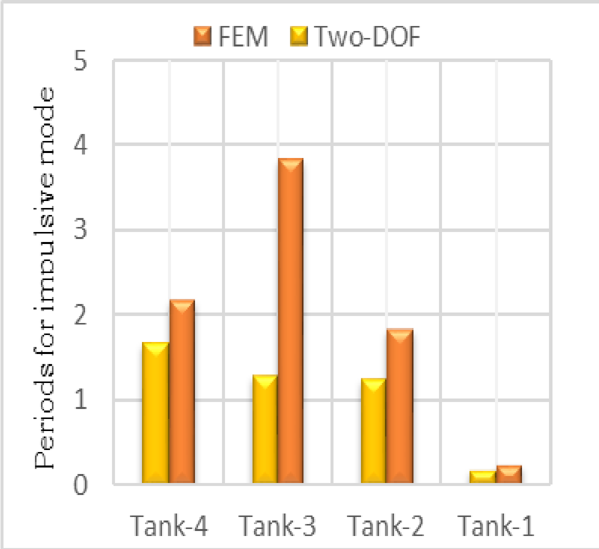


Figure 7. Periods for impulsive mode obtained for four models (Full)

From Figure 6 it is observed the results indicated that T_i for Tank-1, Tank-2, Tank-3 and, Tank-4 based on SDOF idealization instead to Two-DOF and FEM idealizations the percentage of deviations were 34.19%, 27.65%, 228.24% and, 47.65% respectively, which indicates that building the mode according with SDOF inadequacy to calculate T_i particularly in the case of Tank-3 where T_i has decreased abruptly.

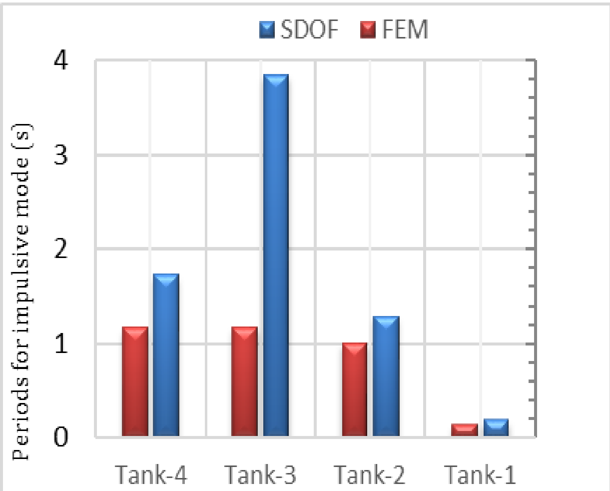


Figure 6. Periods for impulsive mode obtained for four models. (Empty)

For tanks are idealized as Two-DOF (full) for which permits a much closer approximation to the FEM idealization and due to redistributions of the tank masses (water + tank container) the variation results in a decrease for all shapes but still inadequacy, as shown in Figure 7 the deviations for Tank-1, Tank-2, Tank-3 and Tank-4 were 41.05%, 47.24%, 156.56% and. 29.50% respectively, the results also showed that substantial uncertainty to obtained T_i based on Two-DOF for combined conical tank and inapplicability to evaluate T_i through Housner method for this shape of elevated tanks.

For empty tanks as shown in Figure 8, the idealization of tanks based on SDOF shows relatively a marginal different 8.89% in deviation for base shear force when compared to FEM model for Tank-1. Whilst for Tank-2, Tank-3 and Tank-4 where irregularity of mass and stiffness in vertical and their consequences are more severe, the deviations become 21.66%, 78.29% and 41.85% respectively which remarkably far compared to Tank-1.

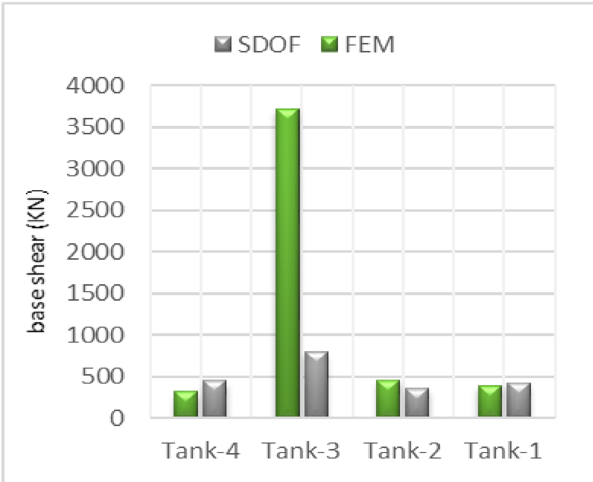


Figure 8. Comparisons of the base shear forces (Empty)

For full condition, the deviation results for Tank-1 and according with SDOF and FEM idealization was found to be 4.7% which shows a relatively good correlation. Whilst based on Two-DOF in which FSI effects are taken into consideration ((the base shear was calculated based on two-mode shapes (convective + impulsive)) the results show a good correlation compared with FEM (3.74%). For Tank-2, Tank-3, and Tank-4 the deviations were found to be 29.88%, 63.48%, and 11.80% for SDOF to FEM and 30.36%, 62.16%, and 29.33% (Figure 9) respectively for accounting FSI into consideration, which means the deviations of base shear for conical shapes are relatively far compared to intze shapes.

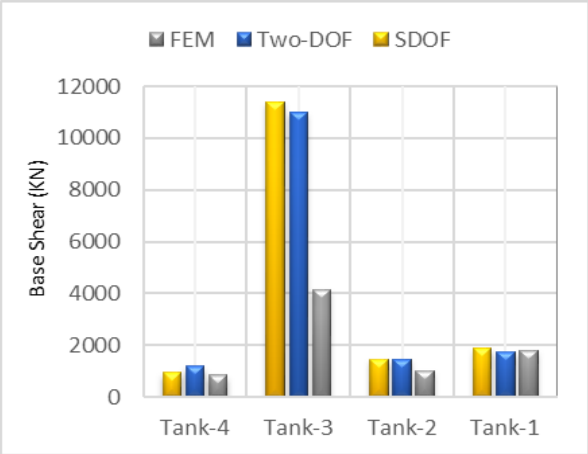


Figure 9. Comparisons of the base shear forces (Full)

Figure 10 and Figure 11 shows almost the same scenario with the overturning moment at the base of the tanks in case of empty or full conditions.

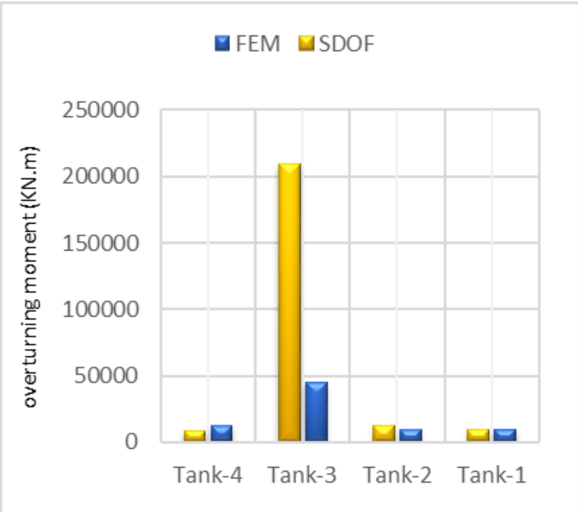


Figure 10. Comparisons of the overturning moment forces (Empty)

Also, from the results obtained note, that the differences between the values of deviations (base shear and overturning moment) are almost equal with differences in the range of 1% either increase or decrease.

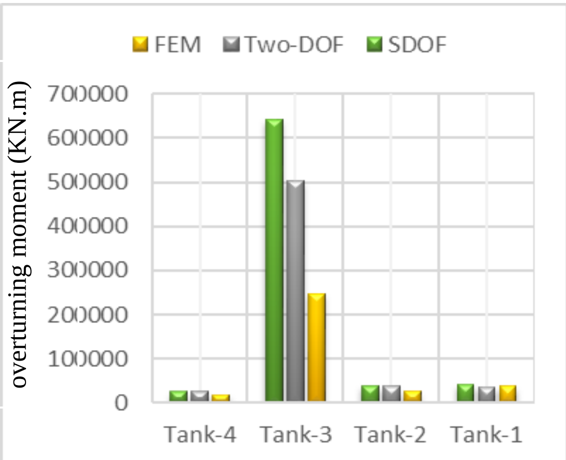


Figure 11. Comparisons of the overturning moment forces (Full)

IV. CONCLUSION

The present study discusses the behavior of elevated tanks under seismic load conditions. Four common configurations of elevated are parametrically investigated. The authors suggest using all of the following techniques to account the seismic effects on elevated tanks.

1- Idealizing the elevated tanks based on a SDOF is still inapplicable for all shapes considered to obtain the base shear and overturning moment at the base of tanks and may remain an overestimate analysis, in full tanks condition.
2- The rather simple model is able to describe the seismic behavior of elevated tanks based on a SDOF for intze tank shape in the case of the empty tank.
3- The simplified procedure that can be utilized for evaluating the dynamic characteristics and the seismic response of the elevated tank is relatively adequate by using two-DOF. Furthermore, analysis with two-DOF procedures, also still also remains some overestimating in case of intze shape.
4- It is inevitable to omit seismic effects for conical, combined conical and cylindrical shapes or sorted into a simpler model by providing mechanical models instead of 3D FEM models of complex elevated tanks and it should be carried out to ascertain true behavior. Although building the model is rather complex through FEM.
5- A lot of work would be needed for these models to be developed to the extent that their real behavior in the variety of possible loads combinations could be realized. It is hoped however that the results to date will give the designers a real insight into their structure and its behavior under load such that they would wish to explore these structures and more fully understand its complexity.

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