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Full Length Research Paper

Parametric study on the effect of burial depth on the surface explosion resistance of cylindrical concrete oil tanks

M. Aboutalebi*, M. R. Banan and M. R. Banan

Department of Civil and Environmental Engineering, Engineering School, Shiraz University, Shiraz, Iran.

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In this paper, the effect of surface explosions on the buried cylindrical concrete oil tanks regarding various parameter changes has been studied. The finite element method has been applied to determine the structural target responses and ANSYS 11.0 macro file was utilized to model more than 7500 models. Moreover, an economical study was performed to prove the favorable effect of increase in the burial depth on the optimum point on the basis of explosion factors and covering soil and structural specifications.

Keywords: Explosion, oil tanks, cylindrical concrete, burial depth.

INTRODUCTION

Oil tanks, as crucial parts of oil production and distribution systems, are highly sensitive to surface explosions caused by either war crafts or civil accidents. In general, embedding the structure into the soil, not only confines the direct impact and heat effects, but also hides it from war crafts.

R/C structures subjected to explosive loadings have been the focus of a significant amount of studies and as such, many experimental and theoretical improvements have been obtained. As recent studies, it can be mentioned to precise measurements of the confining pressure and structural responses of a series of buried frames tested under blast with duration of about 300 ms (Nanjing Engineering Institute, 1987; Zhang et al., 2002), simulation of nuclear explosion condition indicated that the flexural deformation and rigid movement may have an appreciable influence on the structural responses. However, the differences between observed responsive characteristics in the impulsive loading condition are reported. Although several analytical methods have been developed, there are still some uncertainties (Ghaboussi et al., 1984; Krauthammer, 1984; Krauthammer et al., 1986).

The fact that subsequent destruction and casualties of an exploded oil tank might be invaluably more than that to afford for a safe and resistant tank, especially for tanks buried in urban or industrial complexes, accounts for the extra cost of increasing the burial depth of an oil tank regarding the covering soil pressure.

The effects of several parameters as well as burial depth have also been investigated in current study; therefore, the obtained results can be generalized. Moreover, these parameters and their range of variations are presented in the next section.

MODEL DEVELOPMENT AND VALIDATION

Buried oil tanks are usually made of concrete so as to withstand the degrading effects of confining media and become much more resistant against local and extensive buckling. For such a typical structure illustrated in Figure 1, several factors including roof, wall, bottom thicknesses, perpendicular steel ratios, contained oil height, specific mass, crater depth, burial depth, Young's modulus for concrete, soil modulus of elasticity, impulse duration and tank diameter might seem to be the most effective parameters involved. In Tables 1 and 2, the ranges of change of above-mentioned parameters are presented.

In order to consider all these parameters, it is required to generate numerous models. ANSYS 11.0 as a capable tool has been employed to model different effects of explosion, strain hardening, strain softening, crush and crack of concrete under Tresca threshold for combination

*Corresponding author. E-mail: aboutalebi.morteza@gmail.com

Table 1. Material and load properties.

Parameter	Symbol	Unit	Min. value	Max. value	Step	Description
Wave velocity in soil	V_s	m/s	150	550	200	Determines soil elastic modulus
Damping ratio	ζ		5%	20%	5%	Specifies Lagrange multipliers
Oil special weight	γ_o	ton/m^3	0.7	1.2	0.1	
Concrete elastic modulus	E_c	kg/cm^2	150000	350000	50000	
Loading duration	t_L	Sec.	0.0005	0.005	0.00075	
Max. explosive pressure	P_0	bar	10	1000	500	

Table 2. Tank geometry properties.

Parameter	Symbol	Unit	Min. value	Max. value	Step
Reservoir Height	H	m	5	15	2.5
Reservoir Diameter	D	m	15	100	~40
Reservoir Roof Thickness	t_r	m	0.5	2	0.5
Reservoir Wall Thickness	tw	m	0.5	1.5	0.5
Reservoir Bottom Thickness	t_f	m	0.5	2.5	0.5
Column Diameter	D_c	m	0.5	2	0.5
Column Alignment Angle	θc	deg.	15	90	15
Free Board	H_o	m	0	14	4
Circumferential Rebar Ratio	ρ_θ		0.002	0.05	0.008
Vertical Rebar Ratio	ρ_Z		0.002	0.05	0.008
Reservoir Roof Rebar Ratio	$\rho_{\theta r}$		0.002	0.05	0.008
Reservoir Bottom Rebar Ratio	ρ_f		0.002	0.05	0.008
Crater Radius	R_c	m	1	5	2.5
Covering Soil Thickness	H_c	m	1	10	5

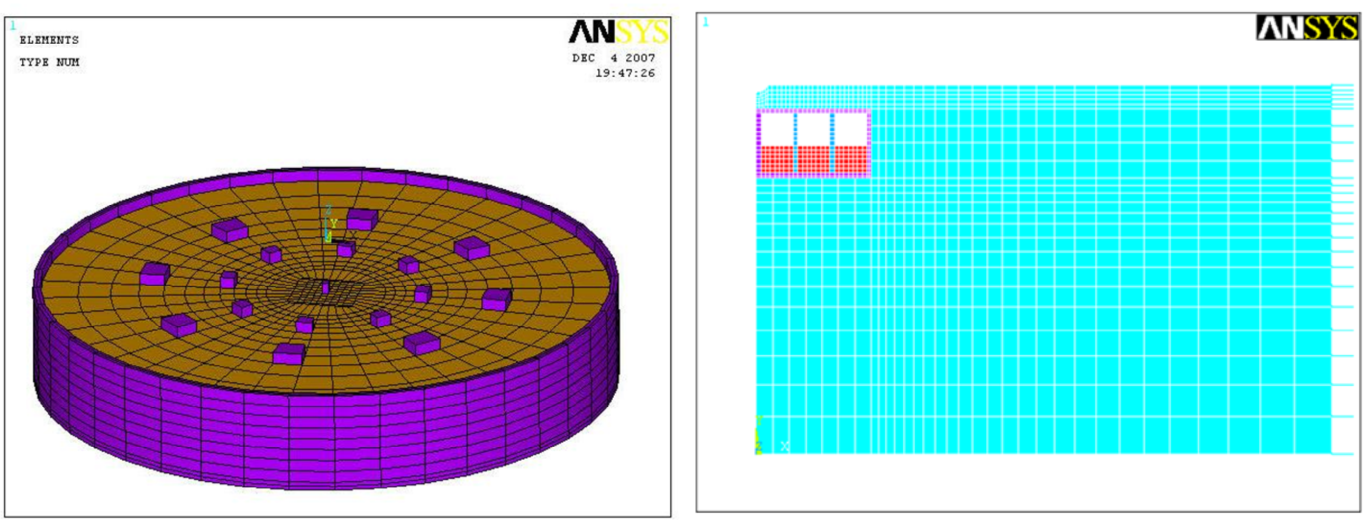


Figure 1. A schematic view of 3D and 2D models.

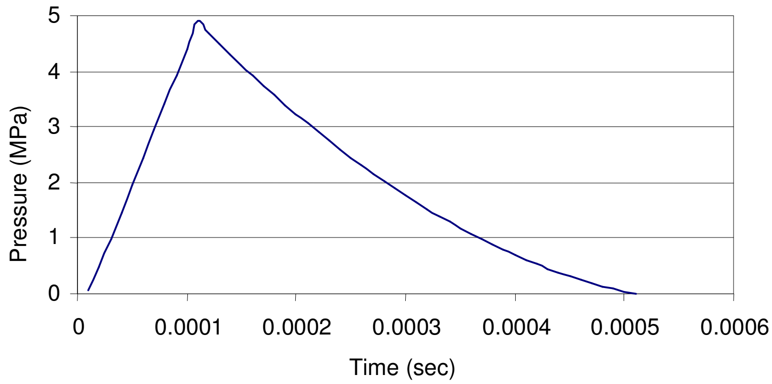


Figure 2. Typical load time history in near field explosion.

of multi-axial stresses. Starting with 3D nonlinear models, all the nonlinear soil-structure and structure-viscous fluid interfaces were implemented using contact-178 element type. This six degree of freedom spring-damper element is also capable to model no-tension property of soil-structure interface surface. The structural elements have been modeled by Solid-65 element type, which is capable of modeling the cracking of concrete based on Tresca threshold. The contained oil was modeled using Fluid-80 element type, a viscous fluid element type, based on Lagrangian fluid analysis method, to produce both deformation and pressure distributions throughout the medium. Solid-45 element type has been employed to model the soil. This element type is capable of modeling linear and nonlinear materials. However, due to the fact that crater was omitted from the model, as a common method, the nonlinear properties were not applied for the sake of process of cost minimization. In addition, the impulse was applied to the crater interior surface. It is accepted in literature that the explosion load time history in near field can be represented as what is illustrated in Figure 2.

As it is shown, the load reaches its maximum value in a very short duration and then falls to zero. For the sake of easy application, the rising part of the time history is normally ignored, however, in the current paper, the complete pattern has been applied. Furthermore, it should be noted that a negative pressure portion must be included to such diagram for non-buried structures, where it is not applicable to buried structures because of no-tension property of the soil. Dampers and springs denoting absorbing boundaries were also applied at the boundary of Soil Island using contact-178 element type to represent an infinite media. In the oil tanks with fixed roof, the free board height was taken in a way that no sloshing wave can splash the roof. Based on the target parameters including tank roof, bottom and side deflections, maximum axial force, shear force, bending moments and pattern of maximum induced pressure distribution on tank roof, the sensitivity of model to mesh sizes in different parts of the model was evaluated. The distributed impulsive pressure on the crater surface representing the explosive effects was controlled by equivalent models in AUTODYN. Also the behavior of viscous fluid used to model the contained oil was checked by simpler models in FLUENT.

The minimum computer specifications required that the model to be analyzed within two weeks include 5200 GHz dual core Pentium IV CPU and 52 GB memory. Since numerous models are needed to consider all the affecting parameters, it is not physically possible to develop and extract the results of all those models within several years. Thus, the model was simplified step by step based on the conservation of acceptable precision. First, the nonlinear interfaces among soil, structure and fluid were removed. Then, in accord with the symmetry of the system and loadings, an axisymmetric 2D model was developed which could be analyzed in less than 15 min and 500 MB of database was produced. The worst relative error of obtained target parameters did not exceed 7%, which is an acceptable inaccuracy. It should be mentioned that in the 2D analysis, Plane 25 was used instead of both Solid 45 and 65 elements for soil and concrete elements and also Fluid 81 plays the role of Fluid 80 for fluid elements.

A schematic view of 3D and 2D models and their components are presented in Figure 1.

NUMERIC RESULTS

Regarding the numerous models required to conduct parametric study, a macro file for ANSYS was prepared to automate the procedure. Almost 7500 models were analyzed and the results are presented. Since, it seems impossible to present all the diagrams for every target parameter in each part, only a number of diagrams are presented in each part.

Burial depth and thickness of tank bottom, wall and roof

As illustrated in Figure 3, the thickness variation of the

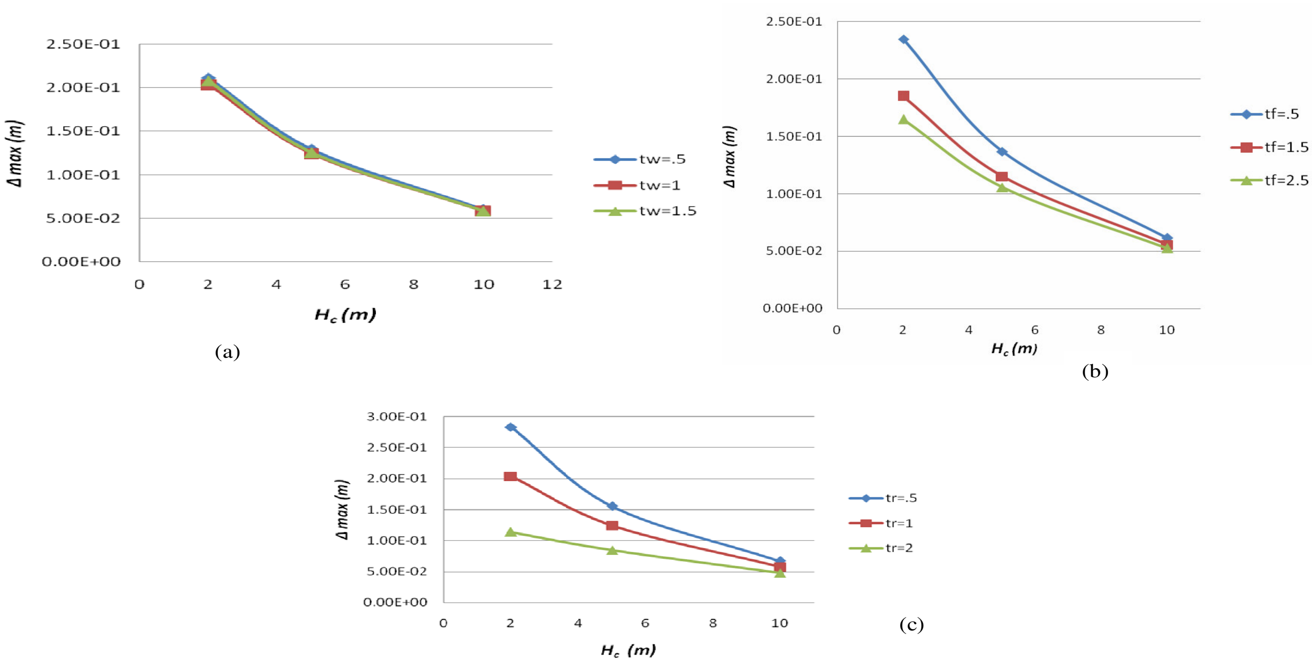


Figure 3. Maximum roof deflections vs. burial depth for (a) wall thickness, (b) bottom thickness and (c) roof thickness variation.

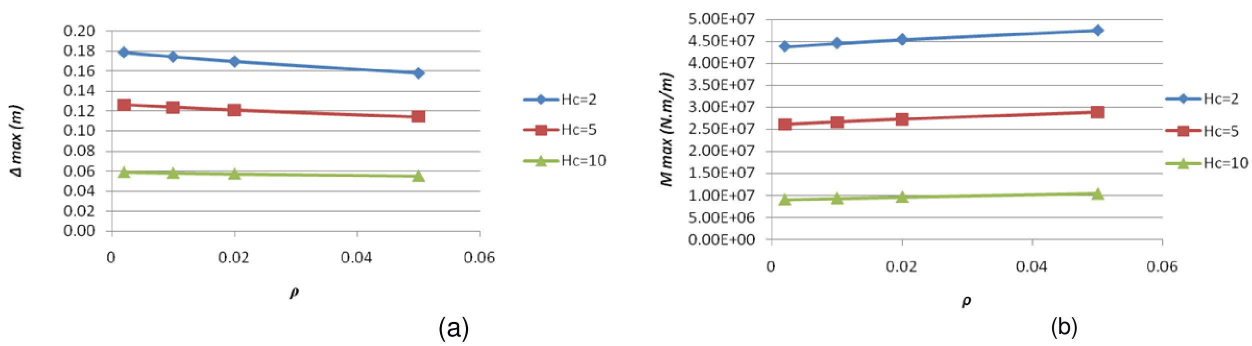


Figure 4. (a) Maximum roof deflections and (b) Maximum roof moments vs. burial depth for variation of steel ratio.

side wall of the tank has negligible effect on the target parameters for any burial depth amount. Whereas, the decreasing deflections versus increasing bottom and specially roof thicknesses indicate that the designer must take care of these factors while repetitive design steps for confining the target design parameters. In general, increasing the thickness of tank roof or bottom results in a considerable cost increase. It should be noted that the reducing effect of increase in the roof or bottom thickness on the target parameters fades out excessively as the burial depth increases.

Burial depth and perpendicular steel ratios in bottom, wall and roof of the tank

From Figure 4, it can be seen clearly that the steel ratios in bottom, top and wall of tank in both perpendicular directions have almost no effect on the target deflections. It can be concluded that although the resistance of tank elements increase as the steel ratio increases, it does not directly affect the amount of design forces and moments. This is a very important result, because the designer will be able to change the amount of steel in each member without worrying about the change of desired capacity of members. Thus, the iterative design procedure does not essentially need repetitive time consuming analyses. If the rebar ratio affected the resulting deflections, internal forces and moments substantially, then it would become essential for the designer to perform an entire analysis of the structure for all load combinations after any rebar designing trial step. This will save much computational effort and reduce the design method to a one step

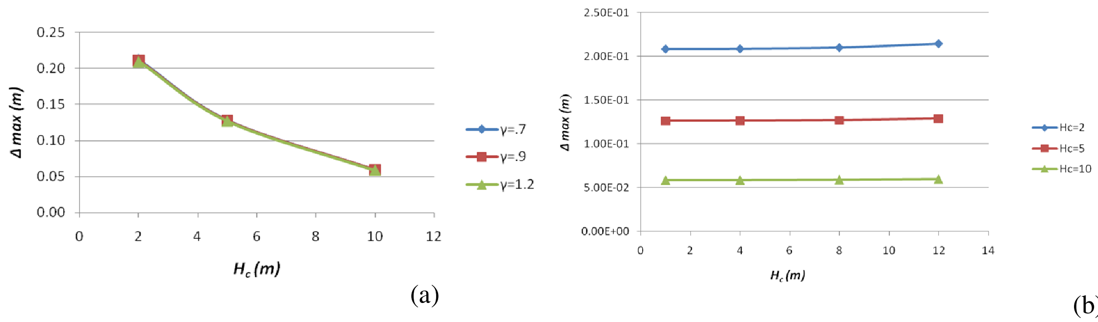
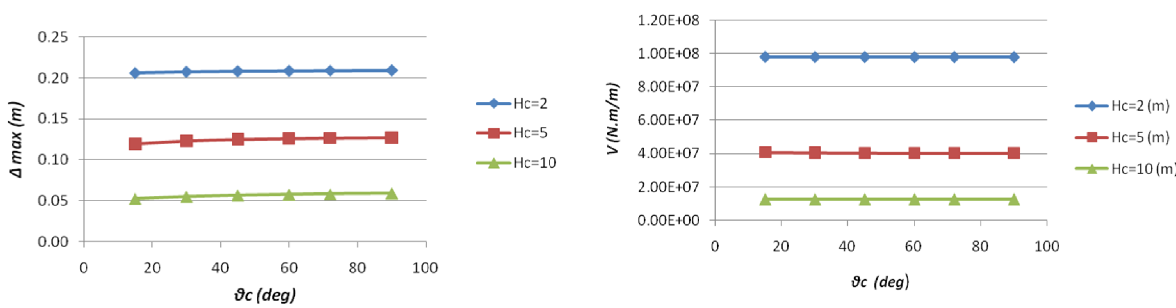


Figure 5. (a) Maximum roof deflections and (b) Maximum roof moments vs. burial depth for variation of steel ratio.



(a) (b)

Figure 6. (a) Maximum roof deflections and (b) Maximum internal roof shear forces vs. column alignment factors.

process.

Contained oil height and specific mass versus burial depth

As it is depicted in Figure 5, the effect of specific mass and variations of oil free board on the all target factors for any burial depth is negligible. The specific mass of crude oil has been assumed to be changeable. This is because, it is not only different for various types of crude oil, but also the tiny floating particles in oil previously sediment in the tank specially while pouring or draining the tank may affect this factor. This is why, when the interface elements in 3D model between structure and contained oil were omitted, negligible error was induced. This is also a very important result, because the designer is not obliged to perform numerous analyses under explosion load case. It is just necessary to add the results of this load case with the results of contained liquid pressure load case which is a considerably easier load case to solve.

Column alignment and burial depth

The central angle between the columns inside the tank (the number of columns on the premiere of the circles specifying the location of each radial row of columns) has been changed and the results for different burial depth as presented in Figure 6. As seen, the angle between columns does not affect the internal forces significantly specially for deeply buried tanks. This is because the maximum target parameters take place near the mid column of the tank based on the location of induced explosion. Hence, this does not imply that the designer should not consider the effect of this factor on total tank behavior. It will certainly affect the essential roof thickness and rebar ratio, which is a dominant economical concern. Anyway, it must not be ignored that explosion is just one load case and dead or live loads effects will certainly be a direct function of column alignment. Hence the designer is supposed to optimize the structure under service loads economically and then concern the explosion.

Crater depth and burial depth

Different explosive materials and destructive bombes with the same energy release capacity might create different craters from the geometrical point of view. Hence crater radius is not a function of explosion maximum pressure. It is predictable that the crater depth is one of the factors affecting the target parameters significantly as illustrated in Figure 7.

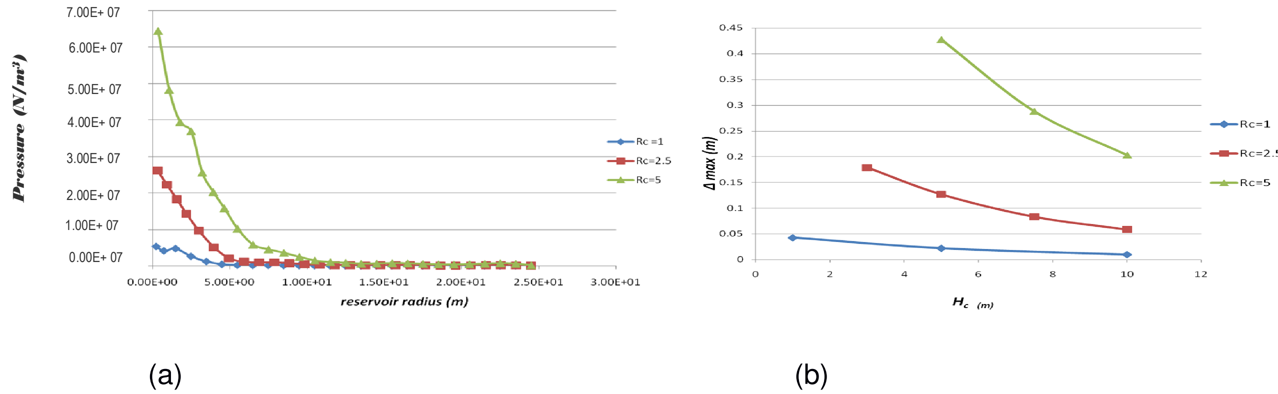


Figure 7. (a) Maximum explosion induced overpressure on roof and (b) Maximum roof deflections vs. crater depth.

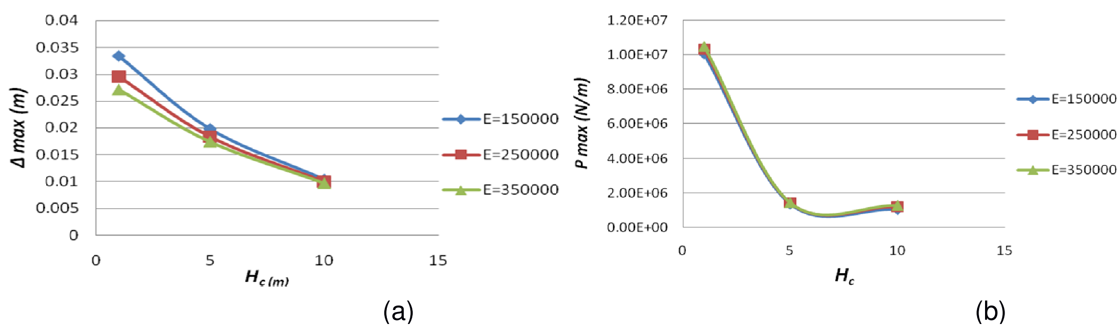


Figure 8. (a) Maximum roof deflections and (b) Maximum roof axial force vs. burial depth for variation of concrete elastic modulus.

In Figure 7, the explosive overpressure distributions on top of an oil tank in various conditions of either the burial depth or crater radius are presented. Although the increase of burial depth decreases the significance of crater radius effect, but the increase of crater depth considerably increases the target parameters.

The extraordinary effect of crater radius makes it obligatory for the designer to predict the geometric crater specifications based on the explosion type and specifications from literature. There are too many references to determine radius and depth of the crater [6~10]. Here, we have assumed the ratio of the depth of the crater to its radius to be equal to 0.6.

Young's modulus for concrete vs. burial depth

Young's modulus of concrete is apparently a function of its strength. For various burial depths, different concrete elastic modulus was studied. However, as it is illustrated in Figure 8, no significant variations in target parameters are noticed. This also may be considered as a significant result because the essential change of material properties during the design does not necessitate the time consuming repetition of analysis.

Soil modulus of elasticity vs. burial depth

The effect of elastic modulus of soil in different burial depth conditions are illustrated in Figure 9. It is obvious that the most considerable effect was observed in bottom deflections. This is because a harder soil will provide a stiffer support for the bottom of the tank. Also the effect on the wall deflections is negligible with respect to roof or bottom deflections, which is reasonable. Stiffer soil with higher modulus of elasticity and consequently higher wave velocity produces a better base for the bottom of the tank, but will concentrate the impulsive overpressure on a smaller zone of the roof. Hence, in order to avoid essential repetitive analyses, the soil type must be determined before design.

Impulse duration and burial depth

There is a direct relation between the duration of explosion and its released energy. Therefore, as can be seen in Figure 10, the linear increase of target parameters in

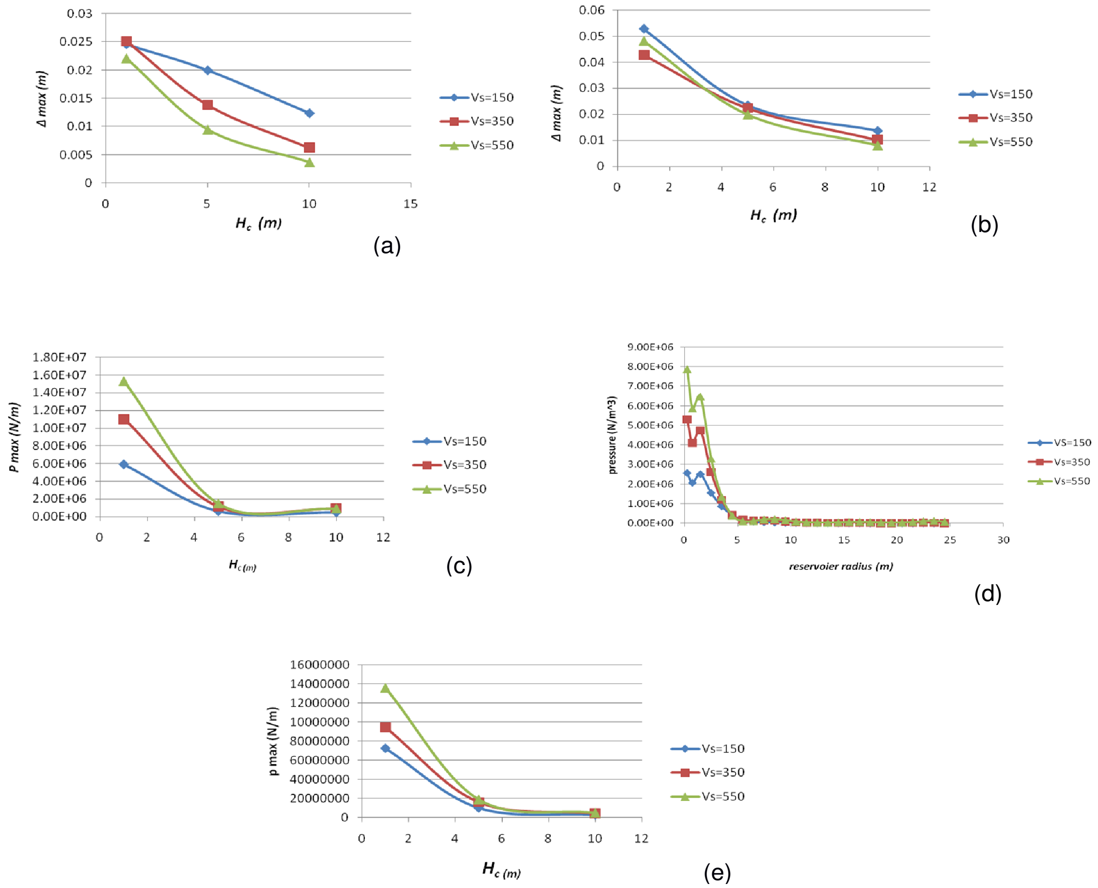


Figure 9. (a) Maximum bottom deflection, (b) Maximum roof deflection, (c) Maximum roof axial force, (d) Maximum central column axial force and (e) impulsive overpressure distribution on roof vs. burial depth for various soil elastic modulus (Here V_s is the shear wave velocity in soil and represents the variation of soil elastic modulus).

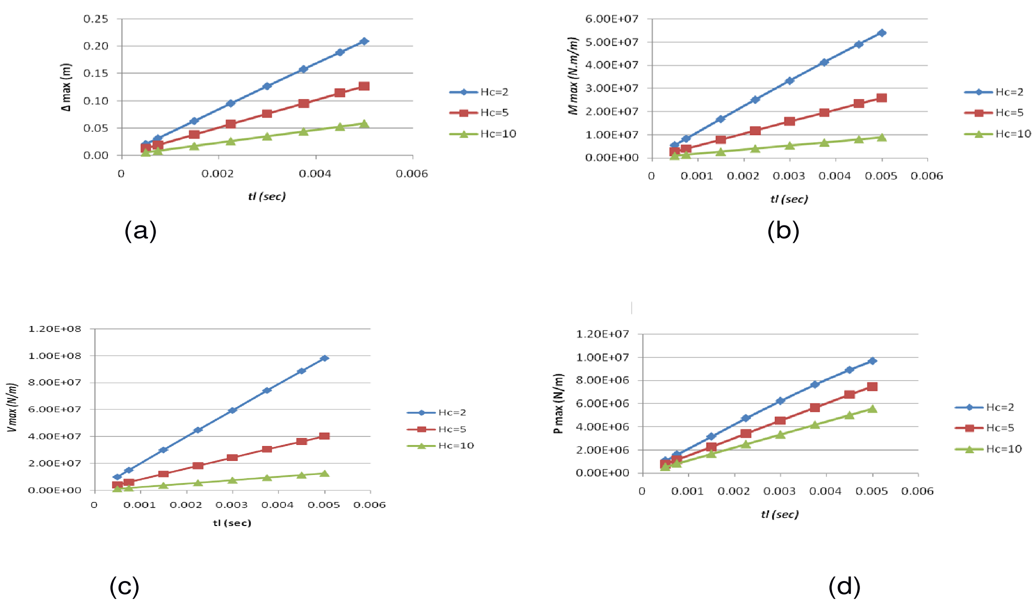


Figure 10. (a) Maximum roof deflections, (b) Maximum roof moments, (c) Maximum roof shear force and (d) Maximum roof axial force vs. impulse duration for variation of burial depth.

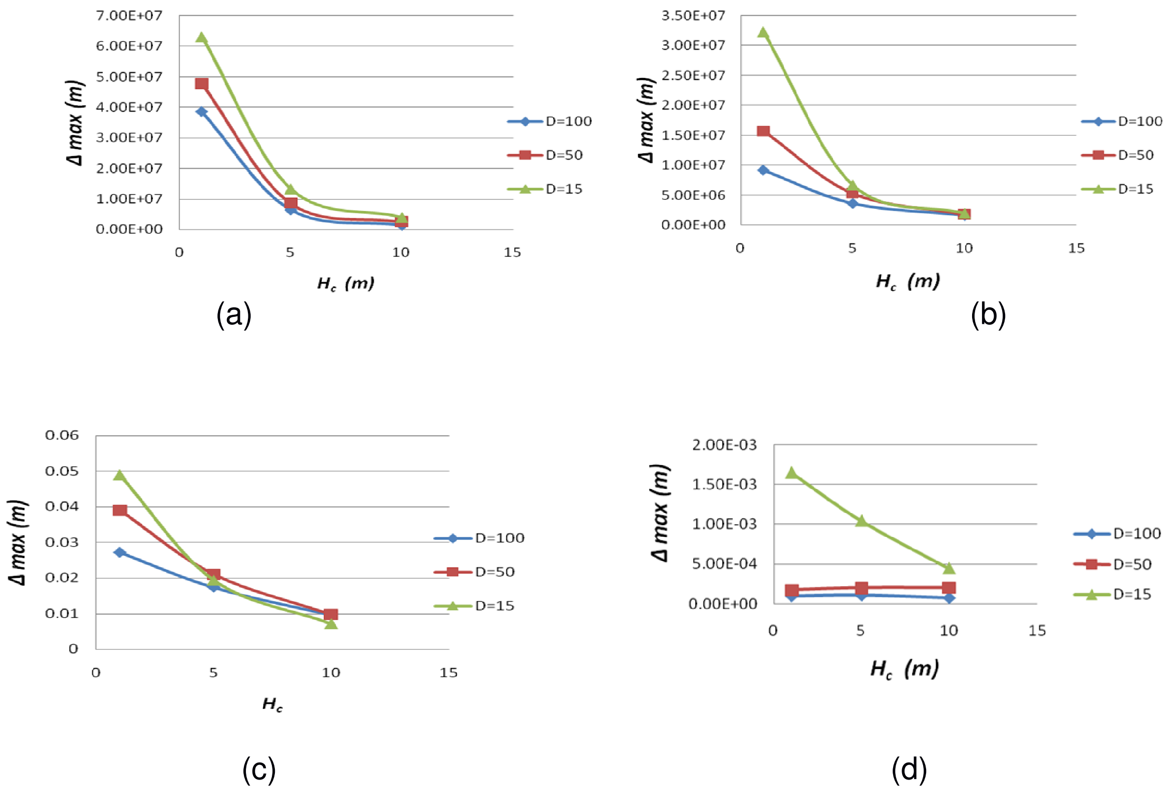


Figure 11. (a) Maximum roof shear force, (b) Maximum roof moment, (c) Maximum roof deflection and (d) Maximum wall deflections vs. burial depth for variation of tank diameter

Table 3. Effects of increase in explosion and dead load.

Burial depth (m)	Maximum moment (t.m/m) under explosion	Maximum moment (t.m/m) under dead load	Maximum shear(t/m) under explosion	Maximum shear(t/m) under dead load
2	4.5E3	4E2	4.8E3	1.7E3
5	2.7E3	1E3	0.8E3	4.2E3
10	1E3	2E3	0.3E3	8.4E3

all burial depths with impulse duration is reasonable. It can be realized that if the impulse energy is maintained constant, increase in the explosion duration will not noticeably affect the structural responses.

Tank diameter and burial depth

It seems clear that burial depth is inversely proportional to the structural responses. However, the maximum shearing force in roof of the tank decreases as the diameter of the tank increases. This can easily be explained by taking a glance on structural behavior. In the tank with larger diameter, the ratio of roof thickness to the distance among the two radial rows of columns decreases. This ratio might be considered as a representative for the stiffness of the roof section among two series of columns, where the maximum roof shear is found. Hence for the tanks with smaller diameters, the stiffness of the roof and consequently the internal forces and moments increase and the deflections decrease, as shown Figure 11.

Economic survey

In order to investigate the economical aspects of the problem, a preliminary assumption for each parameter must be made. The medium value of each parameter used as shown in Table 2 and the models under explosion and dead load due to overburden pressure and structural self weight were developed. The practical burial depth varies from 2 to 10 m. As it is cited in Table 3, the main design parameters without magnifying coefficients based on WSD design philosophy illustrate that an optimum burial depth for this load combination occurs at a burial depth around 5 m. This shows that economically, not only increasing the burial depth to an optimum point decreases the construction cost, but also the thermal and radiation side effects of explosion will not reach the structure and consequently the subsequent implosion in the tank and the consequent vast damage will be quarantined.

Conclusion

The parametric sensitivity analysis presented above showed that among the various factors investigated, burial depth, crater radius and tank diameter play the most important role in determining the structural responses. The crater depth mainly depends on the type and cause of explosion. This evidently proves that for any tank diameter, which is itself, determined by the essential tank capacity, the burial depth must be specified in a way that the combination of design loads containing soil overpressure and explosion induced pressures be optimized.

Also, it was found that the rebar ratio, column alignment and section thicknesses do not substantially affect the analysis results under explosive loads and hence the designer can perform the iterative design procedure needless of repetitive time consuming analysis of the structure under impulsive loads.

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