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The Comparison of DYNA3D to Approximate Solutions for a Partially-Full Waste Storage Tank Subjected to Seismic Loading (U)

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MASTER

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The Comparison of DYNA3D to Approximate Solutions for a Partially-Full Waste Storage Tank Subjected to Seismic Loading

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Introduction

Mathematical solutions to the problem consisting of a partially-full waste tank subjected to seismic loading, embedded in soil, is classically difficult in that one has to address:

- soil-structure interaction
- fluid-structure interaction
- non-linear behavior of materials
- dynamic effects

Separating the problem and applying numerous assumptions will yield approximate solutions. Codes such as SASSI, a 3D soil-structure interaction code, do not address the fluid-structure interaction, interaction between the walls and the soil, non-linear effects, and are limited in the size of the problem (i.e. number of interaction nodes).

Computer programs that address many of these problems are DYNA3D or NIKE3D; the former being an explicit code and the latter an implicit code. Attention in this paper will be focused on DYNA3D and specifically the fluid-structure interaction. A paper by Chen, et. al.,¹ has addressed the effect of soil-structure interaction by comparing AFLUSH, CLASSI, and DYNA3D by relating the Cap model in DYNA3D to the Seed and Idriss model.

Validation problems were developed for SASSI as part of the licensing of the Diablo Canyon Reactor and approved by the Nuclear Regulatory Commission (NRC). These validation problems therefore meet the quality assurance requirements of the Department of Energy (DOE), Westinghouse Savannah River Company (WSRC), and the American National Standards Institute (ANSI) NQA-1 and are acceptable for use at the Savannah River Site (SRS) as

well as other DOE sites. The sample problems in the Users Manual of DYNA and NIKE are illustrative of the type of problems the codes are capable of addressing and to some extent how to prepare the input file. A set of validation problems for the Lawrence Livermore National Laboratory (LLNL) codes in general do not exist nor are the users manuals under document control. The Users Manual for DYNA3D as well as the pre- and post-processors (INGRID and TAURUS respectively), leave much to the analyst depending on which version of the manual one uses. Commercial codes such as ANSYS and ABAQUS have extensive documentation on their use. The Livermore codes, in contrast, are LLNL/DOE codes, and while in the public domain, have limited documentation compared to the commercial codes. While the Livermore manuals are essentially free, the commercial manuals cost approximately \$300.00 per manual. In addition, the staffs in the commercial organizations to validate the codes etc., are significantly larger than the Livermore staff devoted to code development.

DYNA3D was written with the objective of addressing impulsive or explosive type forces and not seismic loading. DYNA would be very appropriate for evaluating the effects of tornadoes on structure. Due to the features of slide surface or slide line capability, developed exclusively at Livermore by John Hallquist, and additional features which include:

- non-linear capability
- pre- and post-processor
- bandwidth minimization
- a valid constitutive relationship for fluids
- an extensive library of constitutive relationships

DYNA contains the nucleus of an attractive code to be used to investigate problems where the emphasis is both soil and fluid structure interaction. In particular, this investigation was undertaken to determine the effect of viscosity which is in the DYNA model and is not addressed in the approximate methods.

The Livermore manuals occasionally describe a capability that is not available in the current source program. For example, the manual describes the use of an 8 node shell element, but this is a degenerate shell element and the shears and moments are not available. The generation of a parabolic surface while in the INGRID manual was not available. We have been advised by telephone by one of Livermore's analysts not to use slice surface capability "1" (i.e. pure sliding without friction) and to use instead slide surface "3" (sliding with friction and separation). The consequence, while we can set the friction to "zero", is that we still have separation. While this is more realistic, it creates difficulty if one is trying to compare the DYNA solution to approximate solutions which do not permit separation.

Some of the parameters used in the manuals are not engineering accepted terminology and to obtain the actual definition one must go to the author. Since Livermore is basically a Physics laboratory, definitions tend to be based more on a physicist's approach than an engineering approach. The origins of the codes were physics problems. The parameter N_{xx} for example in TAURUS is not defined and is not the N defined by Haroun and Housner in their paper on Seismic Design of Liquid Storage Tanks. Another example is V in the material model for DYNA where the definition is "relative volume" rather than the "total volume" used in engineering terminology.

A limitation on the applicability to seismic analysis is the inability of DYNA to respond to a seismic time period of many cycles of reversal of acceleration. After 3 cycles of reaching its peak acceleration, the solution is invalid for the following reasons:

1. The size of the fluid element is incompatible with the frequency content of the time history. Extremely small elements would be required and more nodes needed to define interfaces. This is tractable, but would require more computer time. The calculation for longer time histories becomes much more sensitive and a more refined model is required.
2. The constitutive model of the fluid is not dependent on flow (and time) and is inappropriate for a dynamic calculation.

3. With extensive sloshing, the elements may undergo severe distortion and exceed the capability of the Lagrangian formulation. Eulerian codes are more applicable to problems of this type but are not versatile (i.e., can address simultaneously soil-structure interaction, structure-structure interaction, fluid-structure interaction, as well as structural analyses).

There is no limit to the number of below ground-level nodes that one can have in DYNA3D as distinct from SASSI. In addition, numerous constants are used in the approximate solution which may not be appropriate or as will be shown, vary according to its author. This paper specifically addresses the validation of fluid structure interaction. DYNA3D is a code capable of addressing the entire problem instead of breaking it up into separate processes and therefore should be considered in solving the waste tank problem. One point that should also be considered is that the Livermore codes are owned by DOE and the source programs are available. Unlike commercial codes there is no cost in procuring the codes or in their use. Modifications to the source program are possible and therefore its capabilities can be extended.

The input file to address the fluid structure interaction problem addressed in this paper could not have been undertaken without the consultation of the Livermore staff. In particular, the authors wish to express their appreciation to Dr. Robert Whirley and to Mike Burger of LLNL's engineering staff for their suggestions and assistance.

The Livermore codes do not have validation problems per NQA-1 as was stated, and the time it has taken to complete this analysis exceeded the DOE schedules. DOE and the Waste tank community selected alternate solutions such as the approximate solutions which have had wide acceptance and modeling the fluid in SASSI by replacing it with a mass and a spring to represent the response of the fluid. This paper is an attempt to alleviate the validation requirements of the fluid structure interaction portion of the DYNA code as it is applicable to the waste tank problem and to investigate the effect of viscosity which cannot be addressed by either the approximate solution or the "modified" SASSI approach.

The approximate solution is one developed for flexible partially-filled tanks and referred to as the "Modified Housner Method". These results are compared to an approximate filled flexible tank using the method of Haroun and Housner. DYNA3D calculations were run for a rigid tank, flexible tank, and a flexible tank where only the viscosity has been varied. The DYNA3D results for a rigid and flexible tank partially filled are consistent with the approximate solutions.

Additional calculations were performed with DYNA to evaluate the effect of continued sloshing and distortion of the elements. DYNA3D is limited in that it can only be run for several cycles as was stated. When the number of cycles become greater than 3, the solution does not converge (i.e., the fluid tends to climb the tank walls). Whenever the physical limits are exceeded, the solution also degenerates. The case was run where the top was removed and the walls extended ten feet; this resulted in an unreasonable solution. A slide surface could be inserted between the top of the tank and the top of the fluid surface, but the solution after contact would not be reasonable because of the distortion of the elements after that time.

Problem Description

The problem we are addressing is the waste tank resting on the ground (embedment is not considered) subjected to a horizontal seismic acceleration and gravity. While there are approximate solutions to address two horizontal and one vertical acceleration plus gravity and there is a method to perform the identical calculation using DYNA3D, we chose the single horizontal motion plus gravity. Basically, both the approximate method and the DYNA calculation produce results based on the square root of the sum of the squares of each motion. The model both for the approximate method as well as the computer solution is presented in Figure 1.

Note When considering the flexible case the wall thickness is reduced to 0.052 ft (5/8 in.) and the radius is increased to 42.5 ft.

The seismic load is $\ddot{x}$ based on R. G. 1.60 scaled to 0.2g at 3% damping. The time history is an artificial time history using the computer program SIMQKE.² The model considers the walls and base rigid. The walls, top, and bottom plates, must be modeled as four node shell elements in order to capture the moments and shears. Unlike GEMINI or SAP4 the rotation about the axis normal to the shell surface does not have to be constrained in DYNA or NIKE.

In the case of the top and bottom plates, the normal is the global z axis. In the case of the walls, the normal is always changing and in GEMINI this would be a major effort. In DYNA3D the constraint is automatically addressed once the element is defined as a four node shell element.

While an aspect ratio of 1:1 is preferred, the aspect ratio selected is $< 5 : 1$. More accurate and stable results would be obtained with a 1:1 aspect ratio. However, running time on the computer for a 1:1 aspect ratio would be considerably increased.

Since appropriately, a fluid model is used in DYNA, the standard method of applying gravity cannot be used. Each section of the DYNA3D Manual applied to this problem will be discussed along with its features that are not in the 1989 Manual; this aspect is not addressed in the companion paper on this subject that has been submitted for publication to the American Nuclear Society (ANS). The code INGRID was used to generate the model in Figure 1. The graphics output from INGRID includes node location and identification of slip planes as shown in the attachment. Shell elements were generated by making the walls very thin. In this way an eight node brick repeats with the same initial four nodes for each element. By editing, the second set of four nodes are then deleted. A slide surface is included between the bottom of the fluid and the tank, the sides of the fluid and the tank walls, and between the walls and the top and bottom plates. However, in the case of the walls and the top and bottom plates, we tie shell edge to shell surface (option 7 in the Shell Interface Definitions in the DYNA Manual).

For the purposes of validation the fluid is modeled as water with all the appropriate properties. The model for the fluid is not the same between the approximate solution and the DYNA3D solution and each will be described under the following appropriate sections.

Figure 2a. Modified Housner Method

Figure 2b. Modified Housner Method (Sloshing)

Approximate Solution

From Figure 1 we define $H = 27$ ft, $R = 41.5$ ft. Therefore $H/R = 0.65$ and $R/H = 1.54$. Since $H/R < 1.5$ we use the Modified Housner Method.³ For water, $\gamma = 62.5$ lbs/ft³, $\rho = 1.94 \times 10^{-3}$ mass density, and $W = 9,125$ kips.

The Modified Housner Method considers the hydrodynamic effects to be represented as the sum of the convective and impulsive parts. Following the procedure in reference 3, we first calculate W_1 and two values of h_1 , one excluding dynamic fluid pressure and the other including the dynamic pressure. W_1 is a weight given in Figure 2a and the h 's represent the dimensions which locate the resultant forces.

Using the definitions defined by the Modified Housner Method.

$$W_1 = W \times C_5 \times R/H \times \tanh C_4$$

where C_5 is $0.318 < C_5 < 0.455$

Assuming the value of Veletsos

$$C_5 = 0.455$$

$$W = 9,125, \text{ for water in kips}$$

$$R = 41.5$$

$$H = 27$$

$$C_4 = 1.84 H/R = 1.17$$

then

$$W_1 = 5260.3 \text{ kips}$$

When the flexible model was considered in DYNA3D, it was necessary to extend the fluid model 1 ft to allow the tank wall to be 0.052 ft. This made $R = 42.5$, ft rather than 41.5 ft and the approximate results will differ slightly.

For $R = 41.5$ ft

$$\frac{h_1}{H} = 1 - \frac{\cosh C_4 - 1}{C_4 \sinh C_4} = 0.550 \text{ Excluding Bottom Pressure (EBP)}$$

$$\frac{h_1}{H} = 1 - \frac{\cosh C_4 - 2.01}{C_4 \sinh C_4} = 1.143 \text{ Including Bottom Pressure (IBP)}$$

$$\begin{aligned} \text{then } h_1 &= 0.550 \times 27 = 14.9 \text{ EBP} \\ h_1 &= 1.143 \times 27 = 30.9 \text{ IBP} \end{aligned}$$

$$h_o = 0.375 H = 10.125 \text{ EBP}$$

and

$$h_o = H \times 0.125 \left(\frac{4}{C_3} - 1 \right) = 33$$

$$\text{where } C_3 = \frac{\tanh (1.73 R/H)}{1.73 \times R/H} = 0.371$$

$$W_o = C_3 W = 0.371 (9.125 \times 10^3) = 3.4 \times 10^3$$

$$\omega^2 = (1.84 g/R) \tanh C_4 = 1.176$$

$$\omega = 1.08 \text{ rad/sec}$$

$$f = 0.173 \text{ Hz}$$

$$T = 5.78 \text{ sec}$$

Using $B = 0.005$ damping

$$S_{vh} = 3.2 \text{ ft/sec}$$

$$A_1 = S_1/\omega = 2.96$$

$$\theta h = 1.534 (A_1/R) \tanh C_4 = 0.090$$

Then $P_1 =$ convective force

$$= 1.2 W_1 \times \theta h \times \sin \omega t = 5.68 \sin 1.08 t$$

$$d_{\max} = \frac{0.408 \coth C_4}{g/\omega^2 \times \theta h R - 1} = 3.24 \text{ ft}$$

$$V = \text{base shear} = P_o + P_1$$

$$M = \text{overturning moment} = M_o + M_1$$

Consider $\sin \omega t_{\max} = 1.0$

$$\text{then } P_o = \ddot{x} w/g \quad C_3 = 0.2 \times 32.2 w/g \quad C_3 = 677$$

$$\text{and } V = 677 + 568 = 1,245$$

$$M = P_o h_o + P_1 h_1 = 15.3 \times 10^3 \text{ EBP} = 39.85 \times 10^3 \text{ IBP}$$

Therefore we conclude.

$$d_{\max} = 3.24 \text{ ft}$$

$$V_{\max} = 1,245 \text{ kips}$$

$$M_{\max} = 15.3 \times 10^3 \text{ EBP and } 39.9 \times 10^3 \text{ IBP}$$

Note we assumed max C_5 and $\sin \omega t$ max.

It is significant to further note that the only material property of water that is used is mass density. Viscosity, bulk modulus, etc. are not included in the material model used in the Modified Housner Method. The model used in DYNA includes both viscosity and bulk modulus. A concern by DOE is that the material model used in the approximate solutions are not realistic as one would logically feel that viscosity does have an effect. A complete description of the material model used in DYNA is given in the following section on DYNA.

Referring now to Veletsos paper to determine the maximum pressure on the tank walls.⁴

The hydrodynamic pressure $[p(z, \theta, t)]$ exerted against the wall in a rigid tank is:

$$p(z, \theta, t) = \left[C_o(z) \ddot{x}(t) + \sum_{k=1}^k C_k(z) A_k(t) \right] \rho H \cos \theta t$$

where the first term is the impulsive part and the second term the convective part. Note: ρ varies as the cosine function in the circumferential direction.

From Figure 1, $H = 27$ ft, $a = R$, $H/a = 27/41.5 = 0.65$

z/H	C_0	C_1	C_2
0.	0.8	0.85	0.01
0.2	0.77	0.9	0.01
0.4	0.70	1.0	0.02
0.6	0.6	1.05	0.04
0.8	0.4	1.15	0.08
1.0	0	1.3	0.12

The option is available to either use curves in Ref. 4 or compute the values; it was decided in this case to utilize the curves.

Given $\ddot{x}(t) = 0.2 \times 32.2 = 6.44 \text{ ft/sec}^2$

$$A = \frac{2\pi v}{T} = \frac{2\pi 3.2}{5.8} = 3.5$$

$$T_1 = 0.95 \sqrt{a} = 6.1$$

$$H/a = 0.65$$

$$T_1 = 6.1$$

$$A_1(t) = 2.96 \approx 3.0$$

$$T_2 = 48/\sqrt{a} = 3.0$$

$$S_v = 3.2 \text{ Hz}$$

$p(z, t)$ given that $\theta = 0$ the $\cos \theta = 1$

z	p (kips/ft ²)	
0.	0.4	Bottom of Tank
5.5	0.4	
10.8	0.394	
16.2	0.371	
21.6	0.327	Top of Fluid
27	0.222	

For $\theta = 90$, $p = 0$

$$f_2 = \frac{\pi}{2} [\lambda(2) g/a \tanh (\lambda(2) H/a)]^{1/4} = 0.32$$

$$T_2 = 1/f(2) = 3.125$$

Since T_2 was assumed equal to 3.0, the approximation is valid

For the case where:

$R = 42.5$
 $W = 9571 \text{ kips}$
 $W_1 = 5675 \text{ kips}$
 $W_0 = 3551 \text{ kips}$
 $\omega^2 = 1.15$
 $\omega = 1.07$
 $d_{\max} = 3.32 \text{ ft}$
 $P_0 = 710$
 $V = 1323 \text{ kips}$
 $M_{\text{GBP}} = 16.2 \times 10^3$
 $M_{\text{IBP}} = 42.2 \times 10^3$

DYNA3D MODEL

The following specific items must be noted:

- the fluid selected is water
- a slip surface exists between the fluid and the structure
- separation is permitted

The tank is modeled as a rigid elastic material. Since DYNA is explicit, the time step is determined by the program based on the size of the smallest element which would be a shell element. While it is possible to increase the time step by using pseudo properties, one would have to use an elastic plastic model of the material description for the tank.

In this case, the tank was modeled as elastic, and therefore the time step could not be altered and was approximately 0.001 sec. The time history had 20 sec. of motion, 10 sec. of strong motion. Initially, only 4 ft clearance was provided between the top of the tank and the water as shown in Fig. 1, which was based on approximating $d_{\max}$. Since the computer calculation after reaching the peak acceleration (.2g) for the third time exceeded the 4 ft clearance, and as there was no slide surface between the top of the tank and the fluid, the computer calculation went unstable. When the fluid exceeded the 4 ft clearance, it occupied the same space as the tank. Therefore, the calculation had to be terminated after 2 seconds. A slide surface between the top of the fluid and the top of the tank would resolve this problem but not other problems which are inherent after it reaches the 4 ft clearance as discussed earlier.

We will proceed to go through each section of the 1989 Manual and note the features that were used in this calculation which are in general not described in the 1989 or earlier manuals.

The first section are the control cards which dictate the contents of the input file. In this problem, we had 4 materials, (to more easily separate the sections of the tank), 696 nodes, 300 solid elements (to describe the fluid) and 224 4-node shell elements (to describe the structure). Control card #4, had "3" load curves (x, z, gravity), "57" velocity/acceleration boundary condition cards (to give each node on the base $\ddot{x}$, to include $\ddot{y}$ it is repeated, "114", and for $\ddot{x}$, $\ddot{y}$, and $\ddot{z}$ it is "171"), "4" sliding interfaces (2 fluid, 2 between walls and top and bottom plates), and "1" for base acceleration in the z direction (gravity is incorporated in this manner since listing all the nodes of the fluid would be cumbersome and the method usually used is not applicable to fluids). Control card #5 contains a 0.1 sec time step for gathering of data and a 1.0 sec duration of the calculation. Control card #9 was utilized to avoid hourglassing - granted aspect ratios of 1 to 1 would be helpful, but to avoid hourglassing in this problem, the artificial viscosity was changed from the default value to numbers recommended by the Manual.

The subsequent section contains the material properties cards. The tank was modeled as an elastic rigid material whose modulus was that of reinforced concrete and whose Poissons ratio was 0.2. The mass density was 4.65E-03, $E = 432E+03$, Poissons Ratio $\mu = 0.2$. Because it was identified as a 4 node shell element, the material properties are followed with a card which has shear factor (1.0), number of through shell thickness integration points (4), printout option [3, (resultants, stresses at all points)], and quadrature rule [(0, Gauss)]. The subsequent card has the thickness at each node (2 ft). It is possible to put the thickness in elsewhere but it is simplest in this section.

Initially, we had a thickness everywhere equal to 2 ft and made the structure rigid. Then, we kept the top plate and foundation 2 ft and its material description as elastic and of reinforced concrete and changed the thickness of the walls to 0.052 ft and its elastic description to one of steel where its density, modulus, and Poisson's ratio are properties of steel; 15.23E-03, 4.32E+06, 0.28 respectively, in the appropriate units.

The two cards referring to the shear factor etc. and thicknesses must be included after each 4 node shell material description. Finally, we come to the material model for water. In this case, we were advised by LLNL to use material no. 9 with equation of state 1. A simpler model would have been model no. 5, but that model does not contain the viscosity term. In the model used, no. 9, the first card is the mass density, the second card the pressure cutoff (-1.0 k/ft²), and the viscosity (67.2E-05). The equation of state has the bulk modulus (43200.) and the initial relative volume $V_0 = 1.0$ in the appropriate units.

These cards are followed by the node definitions. Both the node definitions and element definitions are obtained from the preprocessor INGRID. The boundary conditions are edited to permit 6 degrees of freedom. The rotations normal to the upper and lower plates are constrained automatically or one designate the appropriate boundary condition (3.), and the nodes for the solid elements are constrained to prohibit any rotations. Two nodes at the base are grounded so that the tank would not have excessive motion. After the node definitions we have the element definitions. The element definitions, must be in the same order as that in the Manual i.e. solid elements come before the 4 node shell elements. In the description of the 4 node shell element, a blank card must follow each element definition. The blank card tells the code to obtain the thickness from the material property cards. if separate thicknesses were required for each element, then these blank cards would be utilized.

The 4 node element description is followed by the time histories or load curves. Load curve 1 is x acceleration in g, load curve 2 is the vertical, z, time history in g's, and load curve 3 is gravity which consists of 4 points describing gravity. Note that since the values are in g's, they must be converted to ft/sec², the units of the program.

In the description of the load curves, the first card contains the load curve number, number of points in the load curve, and the stress initialization. The last entry, stress initialization, has options: 0 for transient analysis only, 1 for stress initialization but not analysis, and 2 applies to both stress initialization and transient analysis. The only option that is available is 0. If you use 2 for example, not only does the option not work, but the termination time is ignored and you lose control of the program. That is, if one is running the problem interactively, none of the sense switches work except sense sw 2 which only tells you the time of the calculation and the dt of the calculation. The program runs on until you either reach the capacity of the Cray memory or break the calculation. When you break the calculation, you will find that no results have been recorded and the plot file is empty. Therefore, one must use option 0 for initialization. This error is in all the Manuals including the last Manual that was published, the May 1991 issue. The time histories are input under the section on "Velocity/Acceleration Specification Cards for nodes and Rigid Bodies". In this section we have the base node number, the load curve number, the applicable degrees of freedom, the all important scale factor, and identification that it is node acceleration. This can be repeated so that 2 horizontal and one vertical acceleration can be input simultaneously.

The following section contains the sliding interface definitions. In this case, we use type no. 7 which ties the shell edge to the shell surface in order to tie the walls to the top and bottom plates. For the interface between the fluid and the tank we use option no. 3, sliding, with friction (.2 for both static and dynamic friction), and separation. Most of the data for this section was provided by the pre-processor INGRID but had to undergo editing because 4 node shell elements were used. Finally, we put in gravity by utilizing the section on base acceleration in the z direction whose load curve is gravity. Note node numbers do not appear here as all nodes are given the -1 g acceleration of gravity. The output file repeats and digests the input file so that reviewing it is helpful in determining the correctness of the input file. Where the input consists of basically data, the output spells out the definition associated with each data entry.

The engineering output from DYNA is generally obtained graphically. The output file from DYNA is a plot file which can be run with the post-processor TAURUS. While one should be able to move the graphics file from the Cray to the VAX noting that the file is a binary file and not an ASCII file, WSRC has been unable to make this work after 2 years. One of the authors regularly transmitted binary files from the Cray at Livermore to the VAX at LBL without any difficulty. Therefore, the graphics results were obtained on the Cray. The TAURUS post-processor on the Cray does not have the versatility of drivers that are on the TAURUS on the VAX. Since we are limited to emulators, we cannot get color on the Cray using TAURUS. This is important in studying contours and fringes.

Comparison of Results

Using TAURUS we can locate the position of the nodes of interest on the bottom plate, the wall, and top of the fluid. At time equal to approximately .57 sec., the peak ground horizontal acceleration is .2 g's. from the time history. Actually, it is several seconds later that the maximum values are obtained as it takes several seconds for the propagation of the wave through the structure and the fluid as the response is not instantaneous. Therefore, all results are obtained for approximately .57 sec. time although there is also a peak at .45 seconds.

The approximate solution assumes a peak acceleration and not a time history. Using $t = .57$, we obtain with TAURUS the slosh height of the water, the shears and moments of the bottom plate, and the pressure exerted along the tank wall. We compare these values to the approximate solutions.

DYNA3D		APPROXIMATE SOL.
VISCOSITY WATER, WALL RIGID (2 FT)		
d_{max}	3.93 ft	3.24 ft
<u>per element max.</u>		
q_{xx}	296 kips	
q_{yy}	298 kips	
q	424 kips	
ΣQ_{xx}	1102 kips	
ΣQ_{yy}	602 kips	
ΣQ	1256 kips	1245 kips (using lower value of C_3 and actual sin wt, this value can be 907 kips)

DYNA	APPROXIMATE SOL.	
<u>per element max.</u>		
M_{xx}	1270 kip ft	
M_{yy}	1070 kip ft	
M_{xy}	2940 kip ft	
ΣM_{xx}	9080 kip ft	
ΣM_{yy}	8520 kip ft	
ΣM_{xy}	418 kip ft	
ΣM	12451 kip ft	M (EBP) 15,300 kip ft M (IBP) 39,850 kip ft
p (z) : $\theta = 0$, t = .57 sec. (rigid tank)		
z = 0	0.8 kips/ft ²	0.4 kips/ft ²
z = 10	0.54	0.4
z = 15	0.254	0.22

Changing the wall thickness to 0.052 ft and the wall material to steel, we obtain the following results.

FLEXIBLE WALLS		
d_{max}	3.69 ft	3.32 ft (Corrected for 1 ft increase in fluid radius, all approx. values)
<u>per element max.</u>		
q_{xx}	277 kips	
q_{yy}	272 kips	
q	389 kips	
ΣQ_{xx}	766 kips	
ΣQ_{yy}	384 kips	
ΣQ	857 kips	1323 kips
<u>DYNA</u>		<u>APPROX. SOL.</u>
ΣM_{xx}	10468 kip ft	
ΣM_{yy}	14640 kip ft	
ΣM_{xy}	0	
ΣM	17900 kip ft	16260 kip ft (EBP), 42240 (IBP)
$W=9571, W_1=5675, W_0=3551,$ $\omega = 1.07, H/R = 0.64,$ $R/H=1.57$		

For a full tank, the approximate results would have higher values than the approximate results for a partially full tank.

Comparing the effect of viscosity, we have

DYNA (HOH, flex.)	DYNA (3500 vis. HOH, flex.)	APPROX.
ΣQ 857 kips	ΣQ 1025 kips	Q 1323 kips
ΣM 17900 kip ft	ΣQ 21213 kip ft	M 16260 kip ft
d_{max} 3.69 ft	d_{max} 3.20 ft	d_{max} 3.32 ft

Several additional DYNA calculations were performed and the results are as follows:

1. When the calculation went past 3 seconds, the fluid (water) exceeded the clearance of 4 ft and the calculation went unstable.
2. When the top was removed, the fluid wanted to flow over the tank, and then the calculation went unstable.
3. When the top was removed and the tank walls were raised an additional ten feet, the calculation ran for 6 seconds and the fluid climbed up the tank wall.

Conclusion and Discussion of Results

This analysis was directed to validation of the fluid structure interaction problem and to investigate the effect of viscosity. The results have shown that the DYNA solutions for both the flexible and rigid tanks are comparable to the approximate solutions. The limitation of DYNA to several cycles of ground motion is consistent with the approximate solution in that in the approximate solution only one frequency is used and the peak acceleration value. If the limitation to DYNA is the material formulation and or the element size, then the problem of running for longer times can be overcome. If however, the distortions are excessive and Lagrangian limit is reached, then the problem may not be solvable. As long as the time history is of sufficient duration to include the fundamental frequency of the system, then the DYNA calculations will give you solutions comparable to the approximate method. A slide surface could be inserted between the top of the fluid and the top plate, however, while the fluid could not penetrate the top plate, the solution obtained would be invalid if there would be severe distortion and the Lagrangian limit reached.

Clearly, the application to tornado analysis where an impulsive force is applied, is not relevant to the problem encountered in fluid structure interaction. The limitations encountered in the fluid structure interaction problem is not applicable to soil structure interaction, for as the structure oscillates it moves the soil and a gap is created between the soil and the structure; the soil does not oscillate with the structure as in the case of the fluid sloshing. Slide surfaces permit separation which is what is expected to happen with soil structure interaction.

The effect of the higher viscosity in DYNA is to reduce the max. slosh height and increase the base shear and moment. This is what one would anticipate with a higher viscosity, however this effect of viscosity is relatively small. The approximate solution which does not address viscosity, produces a higher base shear than the DYNA solution with the higher viscosity, but a lower moment than both comparable DYNA calculation i.e. viscosity of water and that of 3500 times the viscosity of water. The maximum slosh height is closer to the viscous fluid than the viscosity of water. Viscosity appears to have an effect of the order of 16% when one compares the two DYNA calculations. The advantage of using DYNA over the approximate solution is that it not only addresses viscosity, but has the advantage of providing a lot of additional detailed results. The shear, moment, and stresses as well as the strains and displacements are available whereas this level of detail is not available in the approximate calculation. The variation in shear value depending on whether one uses the Veletsos coefficient or Newmark coefficient is greater than differences obtainable in the DYNA calculation. In fact, using a lower coefficient, one obtains results in the flexible case much closer to the DYNA calculation for base shear. On the other hand, the higher value appears to be more consistent with the rigid tank based on the base shear. Hence, the coefficient appears to depend on rigidity of the tank wall which is not addressed in the ASCE reference.

References

1. Chen, J. C., et al., Eight World Conf. on Earthquake Engr., San Francisco, CA, July 21-28, 1984, UCRL 90029.
2. SIMQKE, A Program for Artificial Motion Generation, NISEE/Computer Application, Nov. 1976, Dept. C.E.MIT.
3. Fluid/Structure Interaction During Seismic Excitation, ASCE, 1984, R. P. Kennedy, Chairman.
4. Veletsos, A. S. and J. Y. Yang, Advances in Civil Engineering, ASCE, Engr. Mech. Div. Specialty Conf., 2nd Proc. Adv. in Civil Engr. through Mech. Engr., Raleigh, NC, May 23-25, 1977.

INGRID Code -- Input File

```
c model of the tank
c box y69
dn3d si 1 tied; si 2 tied; si 3 sl; si 4 sl;
dbqt 1
start
c part 1 top cylinder mate 1
  1 3 5 7 9; 1 3 5 7 9; 1 2;
-21.75 -21.75 0.00 21.75 21.75
-21.75 -21.75 0.00 21.75 21.75
-1.0 -1.1
di 1 2 0 4 5; 1 2 0 4 5; ;
sfi -1 -5; -1 -5; ; cy 0 0 0 0 0 1 43.50
mate 1
si 1 1 2 5 5 2 1 m
end
start
c part 2 bottom cylinder mat 2
  1 3 5 7 9; 1 3 5 7 9; 1 2;
-21.75 -21.75 0.00 21.75 21.75
-21.75 -21.75 0.00 21.75 21.75
-34.00 -34.10
di 1 2 0 4 5; 1 2 0 4 5; ;
sfi -1 -5; -1 -5; ; cy 0 0 0 0 0 1 43.50
mate 2
si 1 1 1 5 5 1 2 m
si 1 1 1 5 5 1 4 m
end
c middle cylinder, shell
ld 1 lp 2 42.60 -2.00 42.50 -2.00
ld 2 lp 2 42.50 -2.00 42.50 -33.00
ld 3 lp 2 42.50 -33.00 42.60 -33.00
ld 4 lp 2 42.60 -33.00 42.60 -2.00
part 1 2 3 4 3 1 8
spin 16 360
mate 3
si 1 1 2 2 17 2 1 s
si 1 1 1 2 17 1 2 s
si 2 1 1 2 17 2 3 m
end
start
c fluid elements
  1 2 5 8 9; 1 2 5 8 9; 1 6;
-20.75 -20.75 0.00 20.75 20.75
-20.75 -20.75 0.00 20.75 20.75
-6.00 -33.00
di 1 2 0 4 5; 1 2 0 4 5; ;
sfi -1 -5; -1 -5; ; cy 0 0 0 0 0 1 41.50
mate 4
sii -1 -5; -1 -5; 1 2; 3 s
si 1 1 2 5 5 2 4 s
end
end
```

INGRID Code -- Diagnostic File

of plates = 0
of solids = 524
>>print

part number = 1

nodes	=	130	first =	1	last =	130
plates	=	48	first =	1	last =	48
bricks	=	48	first =	1	last =	48

part number = 2

nodes	=	130	first =	131	last =	260
plates	=	96	first =	49	last =	144
bricks	=	48	first =	49	last =	96

part number = 3

nodes	=	306	first =	261	last =	566
plates	=	160	first =	145	last =	304
bricks	=	128	first =	97	last =	224

part number = 4

nodes	=	462	first =	567	last =	1028
plates	=	180	first =	305	last =	484
bricks	=	300	first =	225	last =	524

>>

INGRID Node Display – Model of Tank

```
di 1d  
>>di 2d  
>>di nodes  
>>p 4  
>>di nodes  
>>di 1d  
>>p 1  
>>
```

INGRID Node Display – Model of Tank

```
>>p 1      c model of the tank
>>p 1      INGRID nodes
>>di nodes display
>>
```

INGRID Node Display – Model of Tank

```
c model of the tank
>>p 1      INGRID nodes
>>di nodes display
>>p 3
>>p 2
>>di nodes display
>>
```

INGRID Code – Display of Slip Planes

```
p 4
>>di nodes display
>>rx 180
>>di nodes display
>>di si
sliding interface #:3
m or s:s
>>di si
sliding interface #:4
m or s:s
>>wtdb
Taurus database written into file i3plot.
>>continue
creating dyna3d input deck
normal termination
FORTRAN STOP
SLLAB1>
```

INGRID Code – Display of Slip Planes – Sliding Interface #1

```
>>p 1
>>di si
sliding interface #:1
m or s:s
>>di si
sliding interface #:1
m or s:m
>>
```

INGRID Code – Display of Slip Planes – Sliding Interface #1, #2

```
>>p 1
>>di si
sliding interface #:1
m or s:s
>>di si
sliding interface #:1
m or s:m
>>p 2
>>di si
sliding interface #:2
m or s:m
>>
```

INGRID Code – Display of Slip Planes – Sliding Interfaces #1, #2, #3

```
>>p 1
>>di si
sliding interface #:1
m or s:s
>>di si
sliding interface #:1
m or s:m
>>p 2
>>di si
sliding interface #:2
m or s:m
>>p 3
>>di si
sliding interface #:2
m or s:m
>>di si
sliding interface #:3
m or s:m
>>
```

INGRID Code – Display of Slip Planes – Sliding Interfaces #1, #2, #3, #4

```
sliding interface #:1
m or s:m
>>p 2
>>di si
sliding interface #:2
m or s:m
>>p 3
>>di si
sliding interface #:2
m or s:m
>>di si
sliding interface #:3
m or s:m
>>p 4
>>di si
sliding interface #:4
m or s:m
>>di si
sliding interface #:4
m or s:s
>>disi
polygon size:x
```

```
error - expecting a floating point number
line number = 0
error trace:
polygon size:1.0
>>di si
sliding interface #:3
m or s:s
>>
```

INGRID Code – Rigid Tank – Verification of Fluid Structure

Time = 0.57 seconds

contour	value
A=	2.27E-01
B=	4.49E-01
C=	5.72E-01
D=	6.94E-01
E=	8.16E-01
F=	9.39E-01
G=	1.06E+00
H=	1.18E+00
I=	1.31E+00
J=	1.43E+00
K=	1.55E+00
L=	1.67E+00
M=	1.80E+00
N=	1.92E+00
O=	2.04E+00
P=	2.16E+00
Q=	2.29E+00
R=	2.41E+00
S=	2.53E+00
T=	2.65E+00
U=	2.78E+00
V=	2.90E+00
W=	3.02E+00
X=	3.14E+00
Y=	3.27E+00
Z=	3.39E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Z-displacement

Time = 0.57 seconds

```

model of the tank, verification of fluid struct
device number 7
time 0.57000E+00
rx 30 ry 30 rz 20
state 1 min= 0.552E+00 in element 285
time = 0.00000E+00
view
p 4
view
time .57
time = 0.57000E+00
contour 19

```

contour values

1	0.552E+00
2	1.104E+00
3	1.656E+00
4	2.208E+00
5	2.760E+00
6	3.312E+00
7	3.864E+00
8	4.416E+00
9	4.968E+00
10	5.520E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Z-displacement

Time = 0.57 seconds

```

model of the tank, verification of fluid struct
device number 2
time = 0.57000E+00
rx 30 ry 30 rz 20
state 1
time = 0.57000E+00
min = 0.552E+00 in element 285
time = 0.00000E+00
max = 3.64E+00 in element 16
view
p 4
view
time .57
time = 0.57000E+00
contour 19
rx 90
view
contour 19

```

contour values

1	0.36E+01
2	1.19E+00
3	1.54E+00
4	1.89E+00
5	2.24E+00
6	2.59E+00
7	2.94E+00
8	3.29E+00
9	3.64E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Z-displacement

Time = 0.57 seconds

.rz 90
.view
.rz -90
.rx 90
.view
.numcom 20
.contour 19

model of the tank, verification of fluid struct
time = 0.57000E+00
contours of z-displacement
min= 0.552E+00 in element 285
max= 0.292E+01 in element 16

contour values
0.552E+00
0.619E+00
0.666E+00
1.13E+00
1.22E+00
1.49E+00
1.65E+00
1.82E+00
1.99E+00
2.16E+00
2.32E+00
2.49E+00
2.66E+00
2.82E+00
2.99E+00
3.16E+00
3.32E+00
3.49E+00
3.66E+00
3.82E+00

disp. scale factor = 0.400E+01

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Shear Resultant (qxx)

Time = 0.57 seconds

```
.rz 90
.view
.rz -90
.rx 90
.view
.numcom 20
.contour 19
.p 2
.view
.dsrf 1.0
.contour 29
```

model of the tank, verification of fluid struct
time = 0.57000E+00
contours of shear resultant-qxx
min=-0.287E+03 in element 62
max= 0.286E+03 in element 83

contour values
A=-0.71E+02
B=-0.12E+02
C=-2.14E+02
D=-1.03E+02
E=-1.57E+02
F=-1.29E+02
G=-1.00E+02
H=-7.10E+01
I=-4.34E+01
J=-1.50E+01
K=1.34E+01
L=4.18E+01
M=7.02E+01
N=9.06E+01
O=1.27E+02
P=1.55E+02
Q=1.84E+02
R=2.12E+02
S=2.41E+02
T=2.69E+02

disp. scale factor = 0.100E+01 (default)

II GRID Code -- Rigid Tank -- Verification of Fluid Structure
Contours of Shear Resultant (qyy)

Time = 0.57 seconds

```
.rz 90
.view
.rz -90
.rx 90
.view
.numcom 20
.contour 19
.p 2
.view
.dsf 1.0
.contour 29
.contour 30
```

```
model of the tank, verification of fluid struct
time = 0.57000E+00
contours of shear resultant-qyy
min=-0.271E+03 in element 77
max= 0.258E+03 in element 68
```

contour values

1	0.00E+00
2	0.00E+00
3	0.00E+00
4	0.00E+00
5	0.00E+00
6	0.00E+00
7	0.00E+00
8	0.00E+00
9	0.00E+00
10	0.00E+00
11	0.00E+00
12	0.00E+00
13	0.00E+00
14	0.00E+00
15	0.00E+00
16	0.00E+00
17	0.00E+00
18	0.00E+00
19	0.00E+00
20	0.00E+00
21	0.00E+00
22	0.00E+00
23	0.00E+00
24	0.00E+00
25	0.00E+00
26	0.00E+00
27	0.00E+00
28	0.00E+00
29	0.00E+00
30	0.00E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Node Numbers

Time = 0.57 seconds

```

ndplt      model of the tank, verification of fluid struct
           time = 0.57000E+00
node numbers
  
```

dlep. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of X-stress

Time = 0.57 seconds

model of the tank, verification of fluid struct
time = 0.57000E+00
contours of x-stress
min = -0.477E+01 in element 97
max = 0.100E+01 in element 792

contour values

R =	2.58E-01
S =	3.44E-01
T =	0.38E-01

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Moment Resultant (mxx)

Time = 0.57 seconds

displ. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Moment Resultant (myy)

Time = 0.57 seconds

contour 27 model of the tank, verification of fluid struct
time = 0.57000E+00

contours of moment resultant myy
min = -0.742E+03 in element 57
max = 0.107E+04 in element 68

contour	value
1	0.000E+00
2	0.000E+00
3	0.000E+00
4	0.000E+00
5	0.000E+00
6	0.000E+00
7	0.000E+00
8	0.000E+00
9	0.000E+00
10	0.000E+00
11	0.000E+00
12	0.000E+00
13	0.000E+00
14	0.000E+00
15	0.000E+00
16	0.000E+00
17	0.000E+00
18	0.000E+00
19	0.000E+00
20	0.000E+00
21	0.000E+00
22	0.000E+00
23	0.000E+00
24	0.000E+00
25	0.000E+00
26	0.000E+00
27	0.000E+00
28	0.000E+00
29	0.000E+00
30	0.000E+00
31	0.000E+00
32	0.000E+00
33	0.000E+00
34	0.000E+00
35	0.000E+00
36	0.000E+00
37	0.000E+00
38	0.000E+00
39	0.000E+00
40	0.000E+00
41	0.000E+00
42	0.000E+00
43	0.000E+00
44	0.000E+00
45	0.000E+00
46	0.000E+00
47	0.000E+00
48	0.000E+00
49	0.000E+00
50	0.000E+00
51	0.000E+00
52	0.000E+00
53	0.000E+00
54	0.000E+00
55	0.000E+00
56	0.000E+00
57	-0.742E+03
58	-0.500E+03
59	-0.250E+03
60	0.000E+00
61	0.250E+03
62	0.500E+03
63	0.750E+03
64	1.000E+03
65	1.250E+03
66	1.500E+03
67	1.750E+03
68	2.000E+03
69	2.250E+03
70	2.500E+03
71	2.750E+03
72	3.000E+03
73	3.250E+03
74	3.500E+03
75	3.750E+03
76	4.000E+03
77	4.250E+03
78	4.500E+03
79	4.750E+03
80	5.000E+03
81	5.250E+03
82	5.500E+03
83	5.750E+03
84	6.000E+03
85	6.250E+03
86	6.500E+03
87	6.750E+03
88	7.000E+03
89	7.250E+03
90	7.500E+03
91	7.750E+03
92	8.000E+03
93	8.250E+03
94	8.500E+03
95	8.750E+03
96	9.000E+03
97	9.250E+03
98	9.500E+03
99	9.750E+03
100	1.000E+04

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Contours of Moment Resultant (mxy)

Time = 0.57 seconds

contour 28 model of the tank, verification of fluid struct
time = 0.57000E+00

contours of moment resultant-mxy

min=-0.286E+03 in element 85
max= 0.294E+03 in element 70

contour values

A=-0.69E+02
B=-0.40E+02
C=-2.12E+02
D=-1.03E+02
E=-1.54E+02
F=-1.25E+02
G=-9.67E+01
H=-6.88E+01
I=-3.93E+01
J=-1.86E+01
K=1.81E+01
L=4.68E+01
M=7.35E+01
N=1.04E+02
O=1.39E+02
P=1.62E+02
Q=1.90E+02
R=2.19E+02
S=2.48E+02
T=2.76E+02

displ. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Surface Stress

Time = 0.57 seconds

contour 39 model of the tank, verification of fluid struct
time = 0.57000E+00

surface stress $nxy/t + 6*mxy/(t+t)$
min = -0.124E+03 in element 155
max = 0.137E+03 in element 159

contour values
A = -1.05E+02
B = -7.99E+01
C = -5.52E+01
D = -3.06E+01
E = -5.92E+00
F = 1.07E+01
G = 4.34E+01
H = 6.80E+01
I = 9.27E+01
J = 1.17E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Surface Stress

Time = 0.57 seconds

.contour 37 model of the tank, verification of fluid struct
time = 0.57000E+00

surface stress $\sigma_{yy}/t + 6\sigma_{xy}/(t\sqrt{r})$

min = -0.135E+03 in element

max = 0.345E+03 in element

contour values

A = -6.15E+01

B = 2.17E+01

C = 1.05E+02

D = 1.00E+02

E = 2.71E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Rigid Tank – Verification of Fluid Structure
Surface Stress

Time = 0.57 seconds

contour 37 model of the tank, verification of fluid struct
time = 0.57000E+00
surface stress $\sigma_{yy}/t + 6\sigma_{xy}/(t\alpha)$
min = -0.185E+03 in element 1000
max = 0.245E+03 in element 1000

contour values
A = -9.93E+01
B = -5.59E+01
C = -8.53E+00
D = 2.69E+01
E = 8.23E+01
F = 1.28E+02
G = 1.73E+02
H = 2.18E+02
I = 2.64E+02
J = 3.09E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Node Numbers

Time = 0.57 seconds

ndplt
.p 2
.ndplt

model flex. tank, verification of fluid struct
time = 0.57000E+00
node numbers

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of X-displacement

Time = 0.57 seconds

.contour 28 model flex. tank, verification of fluid struct

.contour 17 time = 0.57000E+00

contours of x-displacement

min= 0.193E+01 in element 94

max= 0.202E+01 in element 52

contour values
1. 94E+00
1. 95E+00
1. 96E+00
1. 97E+00
1. 98E+00
1. 99E+00
2. 00E+00
2. 01E+00
2. 02E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of X-displacement

Time = 0.57 seconds

.contour 17 model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of x-displacement
min= 0.141E+01 in element 208
max= 0.207E+01 in element 55

contour values
1.46E+00
1.52E+00
1.59E+00
1.63E+00
1.71E+00
1.77E+00
1.83E+00
1.90E+00
1.96E+00
2.02E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of X-displacement

Time = 0.57 seconds

contour 17

model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of x-displacement
min= 0.106E+01 in element 281
max= 0.105E+01 in element 512

contour values
1.12E+00
1.20E+00
1.27E+00
1.35E+00
1.42E+00
1.50E+00
1.57E+00
1.64E+00
1.72E+00
1.79E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code -- Flexible Tank -- Verification of Fluid Structure
Contours of Z-displacement

Time = 0.57 seconds

contour 19

model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of z-displacement
min= 0.622E+00 in element 247
max= 0.269E+01 in element 100

contour values
1 0.51E-01
2 1.14E+00
3 1.43E+00
4 1.72E+00
5 2.01E+00
6 2.30E+00
7 2.59E+00
8 2.88E+00
9 3.17E+00
10 3.46E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Z-displacement

Time = 0.57 seconds

.contour 19 model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of z-displacement
min= 0.622E+00 in element 247
max= 0.369E+01 in element

contour values
0.80E+01
1.20E+00
1.52E+00
1.64E+00
1.6E+00
1.48E+00
1.00E+00
1.2E+00
1.4E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Shear Resultant (qxx)

Time = 0.57 seconds

ndplt

.p 2

.ndplt

.contour 29

model flex. tank, verification of fluid struct

time = 0.57000E+00

contours of shear resultant-qxx

min=-0.258E+03 in element 62

max=0.277E+03 in element 77

contour values

1=-2.42E+02
2=-2.16E+02
3=-1.89E+02
4=-1.63E+02
5=-1.36E+02
6=-1.10E+02
7=-8.84E+01
8=-6.63E+01
9=-4.41E+01
10=-2.25E+01
11=4.98E+01
12=7.55E+01
13=1.02E+02
14=1.28E+02
15=1.55E+02
16=1.80E+02
17=2.04E+02
18=2.31E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Shear Resultant (qyy)

Time = 0.57 seconds

.contour 30 model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of shear resultant-qyy
min=-0.310E+03 in element 77
max= 0.272E+03 in element 03

contour values
A= 2.92E+02
B= 2.64E+02
C= 2.55E+02
D= 2.06E+02
E= 1.77E+02
F= 1.48E+02
G= 1.20E+02
H= 9.89E+01
I= 6.21E+01
J= 0.82E+01
K= 4.52E+00
L= 2.43E+01
M= 9.0E+01
N= 0.18E+01
O= 1.11E+02
P= 8.9E+02
Q= 6.0E+02
R= 9.7E+02
S= 2.6E+02
T= 5.5E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code - Flexible Tank - Verification of Fluid Structure
Contours of Normal Resultant (mxx)

Time = 0.57 seconds

contour 31

model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of normal resultant-mxx
min=-0.112E+04 in element 57
max= 0.949E+03 in element 64

contour values
A=-1.05E+03
B=-0.50E+03
C=-0.50E+03
D=-7.48E+02
E=-5.45E+02
F=-5.45E+02
G=-4.41E+02
H=-3.39E+02
I=-2.37E+02
J=-1.34E+02
K=-0.32E+01
L= 7.01E+01
M= 1.72E+02
N= 2.75E+02
O= 3.77E+02
P= 4.79E+02
Q= 5.81E+02
R= 6.83E+02
S= 7.85E+02
T= 8.87E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Normal Resultant (myy)

Time = 0.57 seconds

contour .32 model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of normal resultant-myy
min=-0.102E+04 in element 55
max= 0.872E+03 in element 77

contour values
1.0E+02
1.5E+02
2.0E+02
2.5E+02
3.0E+02
3.5E+02
4.0E+02
4.5E+02
5.0E+02
5.5E+02
6.0E+02
6.5E+02
7.0E+02
7.5E+02
8.0E+02
8.5E+02
9.0E+02
9.5E+02
1.0E+03
1.1E+03
1.2E+03
1.3E+03
1.4E+03
1.5E+03
1.6E+03
1.7E+03
1.8E+03
1.9E+03
2.0E+03
2.1E+03
2.2E+03
2.3E+03
2.4E+03
2.5E+03
2.6E+03
2.7E+03
2.8E+03
2.9E+03
3.0E+03
3.1E+03
3.2E+03
3.3E+03
3.4E+03
3.5E+03
3.6E+03
3.7E+03
3.8E+03
3.9E+03
4.0E+03
4.1E+03
4.2E+03
4.3E+03
4.4E+03
4.5E+03
4.6E+03
4.7E+03
4.8E+03
4.9E+03
5.0E+03
5.1E+03
5.2E+03
5.3E+03
5.4E+03
5.5E+03
5.6E+03
5.7E+03
5.8E+03
5.9E+03
6.0E+03
6.1E+03
6.2E+03
6.3E+03
6.4E+03
6.5E+03
6.6E+03
6.7E+03
6.8E+03
6.9E+03
7.0E+03
7.1E+03
7.2E+03
7.3E+03
7.4E+03
7.5E+03
7.6E+03
7.7E+03
7.8E+03
7.9E+03
8.0E+03
8.1E+03
8.2E+03
8.3E+03
8.4E+03
8.5E+03
8.6E+03
8.7E+03
8.8E+03
8.9E+03
9.0E+03
9.1E+03
9.2E+03
9.3E+03
9.4E+03
9.5E+03
9.6E+03
9.7E+03
9.8E+03
9.9E+03
1.0E+04

disp. scale factor = 0.100E+01 (default)

Time = 0.57 seconds

[illegible]

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Moment Resultant (mxx)

Time = 0.57 seconds

.contour 26 model flex. tank, verification of fluid struct

time = 0.57000E+00

contours of moment resultant-mxx

min=-0.202E+02 in element 51

max= 0.152E+04 in element 62

contour values

1.14E+01
1.40E+01
1.50E+01
1.51E+01
1.76E+01
1.21E+02
9.67E+02
1.11E+03
1.26E+03
1.40E+03

displ. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Moment Resultant (myy)

Time = 0.57 seconds

cont.our 27 model flex. tank,verification of fluid struct
time = 0.57000E+00
contours of moment resultant-myy
min=-0.770E+02 in element 74
max= 0.152E+04 in element 62

contour values
1 4.80E+01
2 1.95E+02
3 3.47E+02
4 5.00E+02
5 6.52E+02
6 8.04E+02
7 9.56E+02
8 1.11E+03
9 1.26E+03
10 1.41E+03

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure
Contours of Moment Resultant (nxy)

Time = 0.57 seconds

.contour 28 model flex. tank, verification of fluid struct
time = 0.57000E+00
contours of moment resultant-nxy
min=-0.337E+03 in element 79
max= 0.331E+03 in element 64

contour values
A=-2.87E+02
B=-2.24E+02
C=-1.61E+02
D=-0.73E+01
E=-2.45E+01
F=-2.66E+01
G=9.17E+01
H=1.55E+02
I=2.16E+02
J=2.81E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of X-displacement

Time = 0.57 seconds

.contour 17 flex model: 3500xviscosity water 8/16/92
time = 0.57000E+00
contours of x-displacement
min= 0.146E+01 in element 104
max= 0.205E+01 in element 105

contour values
1 1.50E+00
2 1.56E+00
3 1.61E+00
4 1.67E+00
5 1.73E+00
6 1.78E+00
7 1.84E+00
8 1.89E+00
9 1.95E+00
10 2.01E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of X-displacement

Time = 0.57 seconds

.contour 17 flex model: 8500xviscosity water 9/16/92

time = 0.57000E+00

contours of x-displacement

min= 0.112E+01 in element 281

max= 0.174E+01 in element 281

contour values

A=	1.17E+00
B=	1.23E+00
C=	1.29E+00
D=	1.34E+00
E=	1.40E+00
F=	1.46E+00
G=	1.52E+00
H=	1.58E+00
I=	1.63E+00
J=	1.69E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of X-displacement

Time = 0.57 seconds

.contour 17 flex model: 3500xviscosity water 8/16/92
time = 0.57000E+00
contours of x-displacement
min= 0.112E+01 in element 281
max= 0.174E+01 in element 82

contour values
A= 1.17E+00
B= 1.23E+00
C= 1.29E+00
D= 1.34E+00
E= 1.40E+00
F= 1.46E+00
G= 1.52E+00
H= 1.58E+00
I= 1.63E+00
J= 1.69E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Z-displacement

Time = 0.57 seconds

flex model: 3500xviscosity water 3/16/92
time = 0.57000E+00
contours of z-displacement
min= 0.851E+00 in element 247
max= 0.320E+01 in element 124

contour values
11.05E+00
11.00E+00
11.18E+00
11.40E+00
11.70E+00
11.87E+00
11.97E+00
11.96E+00

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Shear Resultant (qxx)

Time = 0.57 seconds

our 29 flex model: 3500xviscosity water 3/16/92
time = 0.57000E+00
contours of shear resultant-qxx
min=-0.282E+03 in element 62
max= 0.247E+03 in element 93

contour values

A	-2.10E+02
B	-1.94E+02
C	-1.70E+02
D	-1.47E+02
E	-1.23E+02
F	-9.82E+01
G	-7.55E+01
H	-5.17E+01
I	-2.80E+01
J	-4.26E+00
K	1.95E+01
L	4.82E+01
M	5.70E+01
N	9.87E+01
O	1.14E+02
P	1.38E+02
Q	1.62E+02
R	1.86E+02
S	2.09E+02
T	2.33E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code - Flexible Tank - 3500 Times Viscosity of Water
Contours of Shear Resultant (qyy)

Time = 0.57 seconds

.contour 30 flex model: 3500xviscosity water 8/16/92
time = 0.57000E+00
contours of shear resultant-qyy
min=-0.329E+03 in element 77
max= 0.202E+03 in element 83

contour values
1.11E+02
2.01E+02
3.0E+02
4.20E+02
5.90E+02
7.59E+02
9.29E+02
1.07E+03
1.26E+03
1.40E+03
1.55E+03
1.765E+03
1.927E+03
2.090E+03
2.27E+03
2.44E+03
2.61E+03
2.74E+03
2.85E+03
2.85E+03
2.65E+03

displ. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Normal Resultant (mxx)

Time = 0.57 seconds

.contour 31 flex model: 3500xviscosity water 3/16/92
time = 0.57000E+00
contours of normal resultant-mxx
min=-0.112E+04 in element 57
max= 0.940E+02 in element 64

contour values
A=-1.05E+03
B=-1.03E+03
C=-0.52E+02
D=-7.50E+02
E=-1.48E+02
F=-1.46E+02
G=-4.44E+02
H=-3.43E+02
I=-2.41E+02
J=-1.89E+02
K=-0.71E+01
L= 6.47E+01
M= 1.67E+02
N= 2.68E+02
O= 1.97E+02
P= 4.72E+02
Q= 7.4E+02
R= 6.76E+02
S= 7.77E+02
T= 0.79E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Normal Resultant (myy)

Time = 0.57 seconds

.contour 32 flex model: 3500xviscosity water 3/16/92

time = 0.57000E+00

contours of normal resultant-myy

min=-0.975E+03 in element 55

max= 0.870E+03 in element 77

contour values

77 1.90E+02
 81 1.00E+02
 80 1.75E+02
 78 1.46E+02
 79 1.55E+02
 76 1.40E+02
 75 1.72E+02
 74 1.21E+02
 73 1.89E+02
 72 1.01E+01
 71 1.74E+00
 70 1.46E+01
 69 1.78E+02
 68 1.87E+02
 67 1.59E+02
 66 1.50E+02
 65 1.41E+02
 64 1.89E+02
 63 1.24E+02
 62 1.15E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Normal Resultant (mxy)

Time = 0.57 seconds

.contour 33 flex model: 3500xviscosity water 3/15/92

time = 0.57000E+00

contours of normal resultant-mxy

min=-0.540E+03 in element 69

max= 0.409E+03 in element 59

element	value
1	1.12E+02
2	1.05E+02
3	1.05E+02
4	1.05E+02
5	1.05E+02
6	1.05E+02
7	1.05E+02
8	1.05E+02
9	1.05E+02
10	1.05E+02
11	1.05E+02
12	1.05E+02
13	1.05E+02
14	1.05E+02
15	1.05E+02
16	1.05E+02
17	1.05E+02
18	1.05E+02
19	1.05E+02
20	1.05E+02
21	1.05E+02
22	1.05E+02
23	1.05E+02
24	1.05E+02
25	1.05E+02
26	1.05E+02
27	1.05E+02
28	1.05E+02
29	1.05E+02
30	1.05E+02
31	1.05E+02
32	1.05E+02
33	1.05E+02
34	1.05E+02
35	1.05E+02
36	1.05E+02
37	1.05E+02
38	1.05E+02
39	1.05E+02
40	1.05E+02
41	1.05E+02
42	1.05E+02
43	1.05E+02
44	1.05E+02
45	1.05E+02
46	1.05E+02
47	1.05E+02
48	1.05E+02
49	1.05E+02
50	1.05E+02
51	1.05E+02
52	1.05E+02
53	1.05E+02
54	1.05E+02
55	1.05E+02
56	1.05E+02
57	1.05E+02
58	1.05E+02
59	1.05E+02
60	1.05E+02
61	1.05E+02
62	1.05E+02
63	1.05E+02
64	1.05E+02
65	1.05E+02
66	1.05E+02
67	1.05E+02
68	1.05E+02
69	1.05E+02
70	1.05E+02
71	1.05E+02
72	1.05E+02
73	1.05E+02
74	1.05E+02
75	1.05E+02
76	1.05E+02
77	1.05E+02
78	1.05E+02
79	1.05E+02
80	1.05E+02
81	1.05E+02
82	1.05E+02
83	1.05E+02
84	1.05E+02
85	1.05E+02
86	1.05E+02
87	1.05E+02
88	1.05E+02
89	1.05E+02
90	1.05E+02
91	1.05E+02
92	1.05E+02
93	1.05E+02
94	1.05E+02
95	1.05E+02
96	1.05E+02
97	1.05E+02
98	1.05E+02
99	1.05E+02
100	1.05E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Moment Resultant (mxx)

Time = 0.57 seconds

.contour 26 flex model: 3500xviscosity water 3/16/92
time = 0.57000E+00

contours of moment resultant-mxx

min=-0.114E+02 in element 51
max= 0.153E+04 in element 62

contour values
1 1.85E+02
2 2.53E+02
3 4.81E+02
4 5.49E+02
5 8.7E+02
6 8.44E+02
7 9.92E+02
8 1.14E+03
9 1.25E+03
10 1.44E+03

displ. scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – 3500 Times Viscosity of Water
Contours of Moment Resultant (myy)

Time = 0.57 seconds

.contour 27 flex model: 3500xviscosity water 3/16/92
time = 0.57000E+00
contours of moment resultant-myy
min=-0.852E+02 in element 74
max= 0.153E+04 in element 62

contour values
1 0.60E+01
2 1.91E+01
3 3.46E+01
4 5.81E+01
5 8.56E+01
6 1.18E+02
7 1.53E+02
8 1.87E+02
9 2.27E+02
10 2.77E+02
11 3.42E+02

disp. scale factor = 0.100E+01 (default)

INGRID Code -- Flexible Tank -- 3500 Times Viscosity of Water
Contours of Moment Resultant (mxy)

Time = 0.57 seconds

contour 28 flex model: B500xviscosity water B/16/92
time = 0.57000E+00
contours of moment resultant-mxy
min=-0.841E+03 in element 79
max= 0.326E+03 in element 81

contour values
A=-2.91E+02
B=-2.20E+02
C=-1.65E+02
D=-1.82E+02
E=-3.89E+01
F=-2.42E+01
G=0.73E+01
H=-1.58E+02
I=-2.11E+02
J=-2.77E+02

displacement scale factor = 0.100E+01 (default)

INGRID Code – Flexible Tank – Verification of Fluid Structure

.ntime 3 3 312 58 277
.nrtime 3 277 58

minimum = -0.9556E+01
maximum = 0.2051E+02

time

name 277 - 58

END

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