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Influence of ISFSI Design Parameters on the Seismic Response of Dry Storage Casks

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ABSTRACT

Many nuclear utilities have considered using upright cask systems for the dry storage of spent nuclear fuel. These casks are in most cases free standing and rest on a reinforced concrete pad in a variety of arrays. Stability requirements to prevent incipient tipping and sliding of the casks are often based on the cask not exceeding specific limits on either the ZPA of the site ground spectrum or the acceleration at the cask/pad interface (top of pad). Implicit in the use of either the ZPA or the acceleration at the top of the pad, is the assumption that the acceleration at the top of the pad is the same as the acceleration at the center of gravity of the cask, and, therefore, no amplification occurs between the top of the pad and the cask's center of gravity. In contrast to this assumption, the author's experience in the evaluation of Independent Spent Fuel Storage Installation (ISFSI) sites has shown that the cask/pad/soil system can significantly amplify the acceleration response at the cask center of gravity to levels well above the acceleration at the top of the pad.

This paper presents the results of an investigation to determine the influence of three parameters on cask response: pad flexibility (i.e., pad thickness), soil properties and cask layout. A total of 16 soil-structure interaction (SSI) analyses were performed with various combinations of these parameters using the SASSI program. The results show that the most important parameter affecting cask response is the out-of-plane flexibility of the pad, and that this parameter can significantly amplify cask acceleration response at the cask center of gravity. Graphs and tables showing the influence of each parameter on response are presented. These results should be helpful to engineers making preliminary or confirmatory seismic response evaluations of ISFSI sites and design parameters. However, it is important to point out that these results only apply to the prediction of the onset of sliding or tipping. Once tipping or sliding has occurred these results no longer apply, and one must perform either an uncoupled linear/non-linear analysis or a coupled non-linear analysis, much like that in NUREG/CR-6865 [6].

INTRODUCTION

Many nuclear facilities are considering upright casks for the dry storage of spent nuclear fuel. The upright cask systems are usually cylindrical in shape and when filled with spent fuel weigh between 100 and 200 tons (890 and 1780 kN). The casks are normally free standing (unanchored) and rest on a reinforced concrete pad. A typical arrangement of casks is shown in Figure 1 and consists of an array of 12 casks on a 32 by 96 foot (11.0 by 29.3 m) pad. Stability requirements to prevent incipient tipping and sliding of the casks during a seismic event are documented in the cask vendor’s Safety Analysis Report (SAR) and NRC Certificate of Compliance (C of C). The stability requirements are often based on the cask not exceeding specific limits on either the ZPA (zero period acceleration) of the site ground spectrum, or the acceleration at the cask/pad interface, the TPA (top of pad acceleration).

Implicit in using either the ZPA or the TPA in calculations for incipient tipping and sliding, is the assumption that the Independent Spent Fuel Storage Installation (ISFSI) pad, supported by soil, behaves as a rigid mat and therefore possesses no out-of-plane flexibility. This assumption is valid for the majority of nuclear power plant structures where relatively thick mats support integral reinforced concrete walls. However, ISFSI pads are relatively thin due to cask design limitations for impact loads from drop or tip-over, and generally do not incorporate integral walls to stiffen the pad. Thus one must either account for the out-of-plane flexibility of the pad or provide proof that it is not an important parameter to the response of the casks.

While the cask itself is rigid (frequency > 33 Hertz), the rigid cask on a flexible pad has a lateral mode natural frequency that is generally low enough to fall within the amplified range of most design ground spectra. One of the significant findings from having performed soil-structure interaction (SSI) analyses of ISFSI sites is the importance of including the out-of-plane flexibility of the pad when evaluating cask response [1].

In addition to pad flexibility, other site and ISFSI design parameters influence cask response, these include soil properties, ground spectrum shape, cask array layout, and the partial arrangement of casks on the pad at any given time. The objective of this paper is to investigate the influence on cask response of three of these parameters; pad flexibility, soil properties and the arrangement of casks, for the cask array layout shown in Figure 1, when subjected to ground motion input enveloping a NUREG/CR-0098 [7] type spectrum.

SITE AND ISFSI PARAMETERS CONSIDERED

Soil Properties

The soil upon which reinforced concrete pad rests consists of a 100 foot (30.5m) deep uniform layered profile with constant shear wave velocity and associated compression wave velocity. Below a depth of 100 feet (30.5m) stiffer soil properties are assumed. In a series of SSI analyses the shear wave velocity is varied from 500 to 1700 fps (152 to 518mps) to assess the influence of soil stiffness on cask response. With each change in shear wave velocity the compression wave velocity is also recalculated. The physical properties of the soil within the 100 foot (30.5m) layer are as follows: Poisson's ratio = 0.40, density = 125 lb/ft^3 (19.6 kN/m^3), and material damping = 2.5 percent.

Pad Flexibility

The reinforced concrete pad has a modulus of elasticity consistent with 3000 psi (20.7MPa) normal weight concrete, a Poisson's ratio of 0.17 and material damping of 5 percent. To evaluate the influence of pad flexibility on cask response, a series of SSI analyses were conducted for pads with thicknesses of 1.5, 2, 3 and 4 feet (0.46, 0.61, 0.91 and 1.22m). Uncracked concrete properties were assumed in all cases. It should be noted that to the authors' knowledge no ISFSI pads have been constructed that are less that two feet thick. However, if concrete cracking is considered, pad flexibility is increased, and an uncracked 1.5 ft (0.46m) thick pad would have roughly the same flexibility as a 2 ft (0.61m) thick pad with a cracked moment of inertia equal to about half the uncracked moment of inertia.

Cask Layout and Cask Properties

The cask array layout considered is a typical configuration found at a number of installations and consists of an array of 12 casks resting on a reinforced concrete pad as shown in Figure 1. Two arrangements of casks were considered. The first case, called the '12-cask case", is the final state in which all 12 casks are on the pad. This represents the situation with the most mass on the pad. To address the issue of a partial arrangement of casks, the second case, called the "3-cask case", consists of a pair of casks (casks 2 and 3 in Fig.1) on one end of the pad and a single cask (cask 10) near the opposite end of the pad. This second case is a reasonable representation of a one and two cask case.

For the purpose of performing SSI analysis, a cask can be represented by three properties: footprint diameter, total weight, and height to the cask center of gravity. For this analysis an average of several vendor's cask properties was used. This "generic" cask has a footprint diameter of 9 ft (2.74m), a total weight of 285,000 lbs (1268kN) and a height to the center of gravity of 8.83 ft (2.69m).

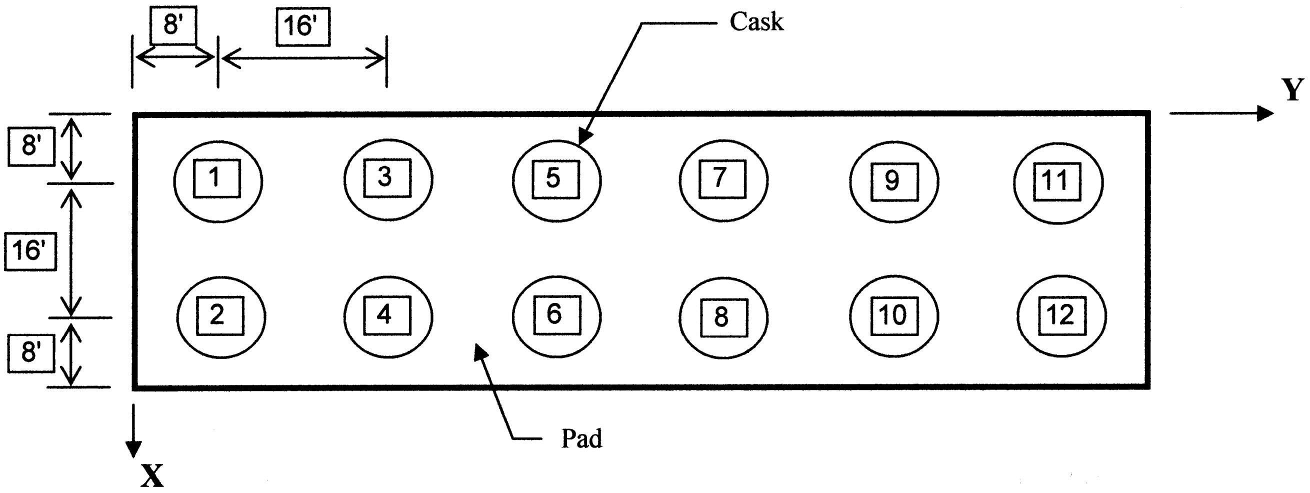

Figure 1: Plan view of the 12-Cask Case

SSI ANALYSIS APPROACH

One of the few readily available SSI analysis programs that can directly account for the out-of-plane flexibility of a concrete pad on soil is the program SASSI (A System for Analysis of Soil-Structure Interaction, [2]). SASSI is a linear analysis program, and since the casks are not mechanically attached to the pad, but are free standing, the effects of cask tipping and sliding cannot be incorporated. This, however, poses no real limitation, provided the dead load precompression of the cask on the pad is not over come by a combination of vertical and horizontal acceleration at the cask center of gravity so as to cause incipient tipping or sliding. This assumption is easily verified later when checking for incipient tipping and sliding as part of the seismic requirements. Even if the analysis shows that moderate sliding or incipient tipping occurs, the SASSI program can generate translation and rotation time histories at the cask base node (top of pad) that can then be used to perform a nonlinear time history analysis using an explicit dynamic analysis program, such as, LS-DYNA [3].

ISFSI Pad Model

The ISFSI pad was modeled using plate finite elements. The mesh was proportioned to accommodate the rigid body cask model at points of contact with the exterior edges of the cask base. A minimum of two plate elements was provided between edges of all adjacent casks, since reverse curvature of the pad was expected to occur between casks. The pad finite element mesh is shown in Figure 2 for the 3-cask case.

Cask Seismic Model

The cask finite element model is composed of beam and truss elements. Elevation and plan views of the cask model are shown in Figure 3. The vertical beam element (the cask beam) connects the cask base node to the center of gravity (CG) of the cask, and was tuned to a frequency of 40 Hertz, which is representative of the frequency of most upright casks and is well within the rigid range (i.e., greater than 33 hertz). The total weight of the cask was lumped at the CG node. From the central base node, 8 rigid horizontal beams span to the edge of the cask. Since the SASSI program does not allow moment end releases at beam element nodes, the cask edge nodes at the ends of the horizontal beams were connected to the pad nodes by vertical truss elements one inch long. The vertical truss elements are very stiff axially to maintain vertical contact between the cask and pad, but do not restrain rotation of the pad. This allows the pad plate elements to rotate beneath the cask edge nodes while still maintaining vertical contact. The properties of the 8 rigid horizontal beams and stiff vertical truss elements are sufficient to maintain the natural frequency of the cask model well within the rigid range.

The vertical truss elements described above provide vertical connectivity with the pad but no lateral restraint. Lateral restraint is provided by orthogonal pairs of horizontal “spring” elements that connect the central base node of the cask to the pad. These spring elements are really beam elements with high axial stiffness and very low bending stiffness so they only provide lateral restraint and do not constrain rotation of the pad.

Using specially developed software, the entire pad and cask finite element model was translated to the general purpose finite element analysis program ANSYS [4]. Several ANSYS static and modal extraction analyses were performed to verify the proper behavior of the pad and cask seismic model and to provide insights into the general behavior of the cask/pad/soil system.

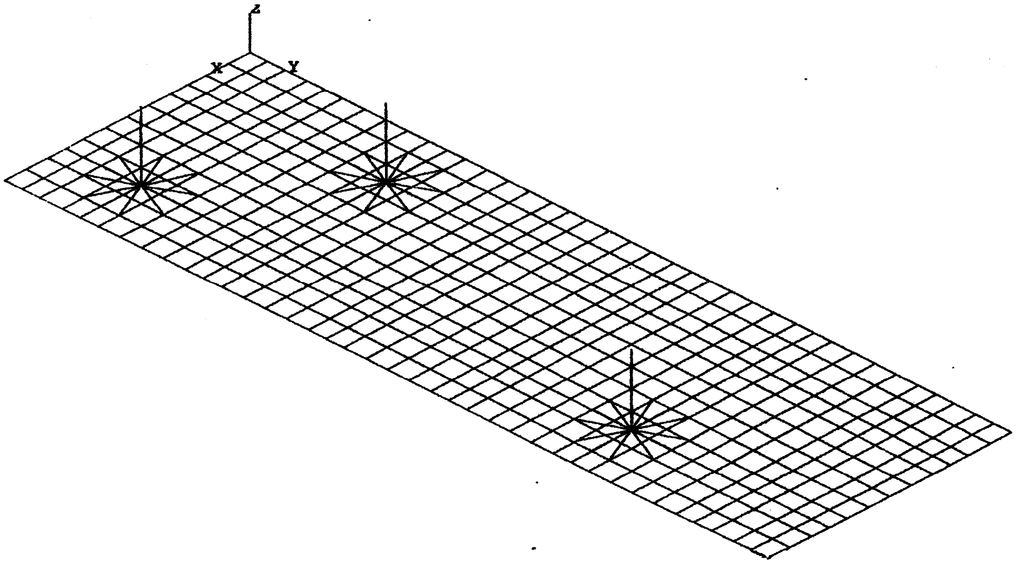

Figure 2: Pad and Cask Finite Element Model for the 3-Cask Case

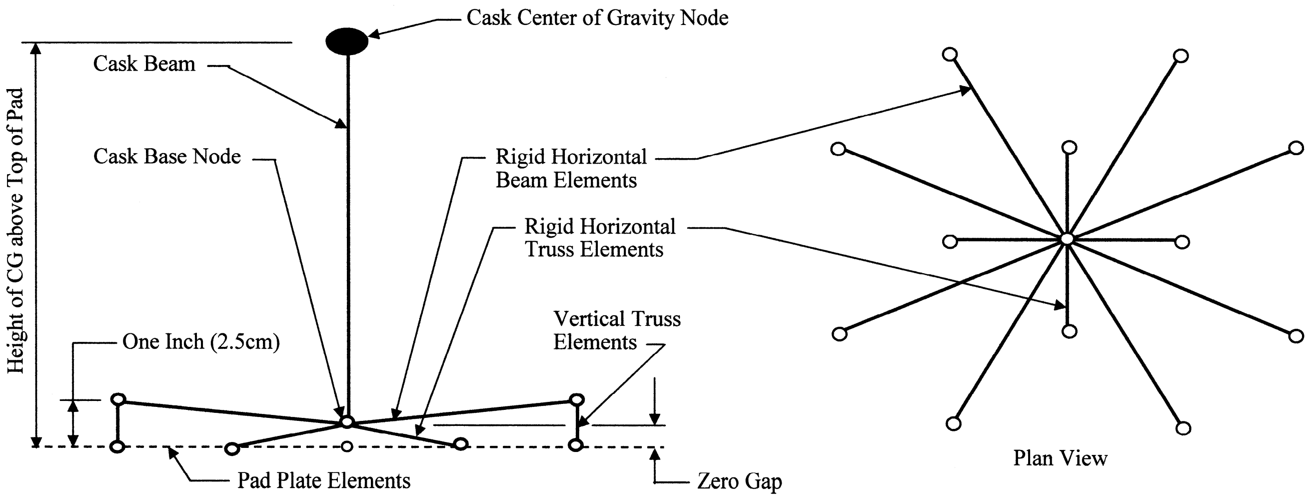

Figure 3; Cask Finite Element Model – Elevation and Plan Views

Ground Motion Input

Because of its broad frequency content and frequent use in the industry, a median centered NUREG/CR-0098 type horizontal spectrum anchored to a peak ground acceleration (PGA) of 0.15g was selected as the ground motion input. The vertical spectrum was set equal to 2/3 of the horizontal ground spectrum with a PGA of 0.10g. The 5% damped horizontal ground spectrum is distinguished by a region of constant amplitude equal to 0.318g between frequencies of 2 and 8 hertz. Thus the ground spectrum has a maximum amplification above the PGA of 2.12. The control point for the ground motion input was chosen to be at the ground surface. The wave composition of the control motion was defined as vertically propagating shear waves and vertically propagating compression waves.

Three acceleration time histories were generated, two horizontal and one vertical. Each time history is approximately 25 seconds in duration. The 5% damped spectrum for each time history closely matched the ground spectrum. In addition, the response spectrum check, the power spectral density check and the cross correlation coefficients all satisfied the latest revision of the NRC Standard Review Plan [5].

SEISMIC RESPONSE RESULTS AND SYSTEM BEHAVIOR

For both the 3-cask and 12-cask layout cases, five SSI analyses were performed for a 2 ft (0.61m) thick concrete pad for soil shear wave velocities ranging from 500 to 1700 fps (152 to 518mps). For the shear wave velocity that produced the highest acceleration response at the cask CG, additional SSI analyses were performed for concrete pad thicknesses of 1.5, 3.0 and 4.0 feet (0.46, 0.91 and 1.22m) for each of the two cask cases. In all a total of 16 SSI analyses were performed. A comprehensive summary of the results is provided in Table 1, which shows the maximum acceleration response of any cask at the cask CG in each direction due to ground motion input only in that direction.

Before discussing the results of Table 1, it is important to make two observations. [Due to space limitations, however, the data supporting these observations cannot be included in the paper.] First, there is virtually no amplification at the base of the cask (top of pad) due to horizontal input in either direction. All of the amplification occurs at the CG node of the cask, and since the cask is rigid, all of the amplification is due to the rotation of the cask resulting from the flexibility of the pad. [This was also borne out by the ANSYS modal extraction analyses.] Second, there is almost no coupling of response among the three input directions and, as such, only the response in the direction of input motion will be reported and discussed. [The combination of directional responses is discussed in Reference 1.]

Table 1 shows that maximum response is dominated by ground motion input in the short (X) direction of the pad, although significant response also occurs in the long (Y) direction as well. The results from Table 1 are plotted in Figures 4, 5, 6 and 7. For the 3-cask case, Figure 4 shows that the maximum amplification of a cask on a 2 ft (0.61m) thick pad occurs at a shear wave velocity of 1100 fps (335mps). Using the 1100 fps (335mps) soil profile with different pad thicknesses, Figure 5 shows the dramatic change in amplification as pad thickness varies. Increasing pad flexibility results in increased amplification. In addition, it is important to note that in all nine SSI analyses for the 3-cask case , the single isolated cask (cask 10) always produced the maximum response.

For the 12-cask case, Figure 6 shows that maximum amplification for a cask on a 2 ft (0.61m) thick pad occurs at a shear wave velocity of 1700 fps (518mps). At first glance this is a somewhat startling result since intuitively we do not expect amplification to be increasing as the stiffness of the soil increases. In order to understand why this occurs we need to distinguish between two phenomenon: soil-structure interaction and beam on elastic foundation behavior, and recognize that both are occurring together to create complex response. As discussed below, it is the latter phenomenon of which we must be most aware.

For the 2 ft (0.61m) thick pad, the increase in soil shear wave velocity from 500 to 1700 fps (152 to 518mps) creates important changes in the static and modal behavior of the cask/pad system on soil. From beam on elastic foundation theory, it can be demonstrated that the influence of any cask’s rotation on the neighboring cask’s response is far more negative at low shear wave velocity than at high shear wave velocity. Thus at lower shear wave velocity there is greater negative cask-cask interaction through the pad than at higher shear wave velocity.

Table 1: Summary of Maximum Directional Response at the Cask Center of Gravity

						Maximum X-Direction Response Due to X-Input Only		Maximum Y-Direction Response Due to Y-Input Only		Maximum Z-Direction Response Due to Z-Input Only	
Analysis Number	Casks on Pad	Shear Wave Velocity		Pad Thickness		Acceleration at Cask CG	Amplification Factor	Acceleration at Cask CG	Amplification Factor	Acceleration at Cask CG	Amplification Factor
		fps	*mps*	*ft*	*cm*	*g's*	*(Note 1)*	*g's*	*(Note 1)*	*g's*	*(Note 1)*
1	3	**500**	152	**2.0**	61	0.212	**1.41**	0.178	**1.19**	0.118	**1.18**
2	3	**700**	213	**2.0**	61	0.229	**1.53**	0.188	**1.25**	0.122	**1.22**
3	3	**900**	274	**2.0**	61	0.238	**1.59**	0.209	**1.39**	0.117	**1.17**
4	3	**1100**	335	**2.0**	61	0.242	**1.62**	0.206	**1.38**	0.113	**1.13**
5	3	**1300**	396	**2.0**	61	0.238	**1.59**	0.209	**1.39**	0.110	**1.10**
6	3	**1700**	518	**2.0**	61	0.220	**1.47**	0.200	**1.33**	0.106	**1.06**
7	3	**1100**	335	**1.5**	46	0.274	**1.83**	0.238	**1.59**	0.115	**1.15**
4	3	**1100**	335	**2.0**	61	0.242	**1.62**	0.206	**1.38**	0.113	**1.13**
8	3	**1100**	335	**3.0**	91	0.192	**1.28**	0.181	**1.20**	0.110	**1.10**
9	3	**1100**	335	**4.0**	122	0.162	**1.08**	0.172	**1.15**	0.111	**1.11**
10	12	**500**	152	**2.0**	61	0.171	**1.14**	0.181	**1.20**	0.104	**1.04**
11	12	**700**	213	**2.0**	61	0.168	**1.12**	0.181	**1.21**	0.115	**1.15**
12	12	**900**	274	**2.0**	61	0.173	**1.15**	0.170	**1.14**	0.109	**1.09**
13	12	**1100**	335	**2.0**	61	0.181	**1.21**	0.173	**1.15**	0.112	**1.12**
14	12	**1300**	396	**2.0**	61	0.192	**1.28**	0.179	**1.19**	0.111	**1.11**
15	12	**1700**	518	**2.0**	61	0.200	**1.34**	0.178	**1.19**	0.111	**1.11**
16	12	**1700**	518	**1.5**	46	0.221	**1.47**	0.194	**1.29**	0.108	**1.08**
15	12	**1700**	518	**2.0**	61	0.200	**1.34**	0.178	**1.19**	0.111	**1.11**
17	12	**1700**	518	**3.0**	91	0.164	**1.09**	0.177	**1.18**	0.110	**1.10**
18	12	**1700**	518	**4.0**	122	0.159	**1.06**	0.169	**1.13**	0.113	**1.13**

(1): Amplification Factor equals maximum acceleration divided by PGA. The PGA = 0.15g for X and Y input and 0.10g for Z input.

Input/Response Directions: X - Pad Short Direction
Y - Pad Long Direction
Z - Vertical

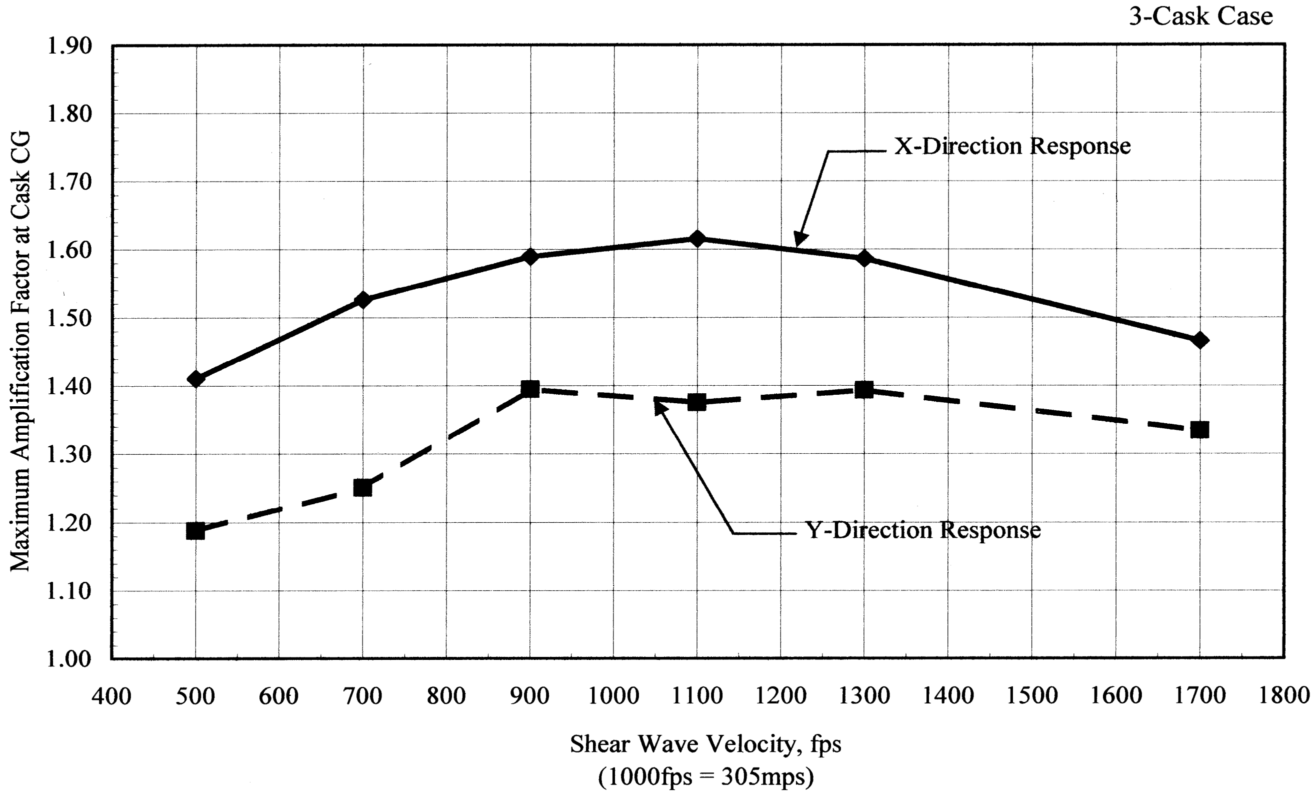

Figure 4: Amplification Factor vs. Shear Wave Velocity for the 3-Cask Case for a 2 foot Thick Pad

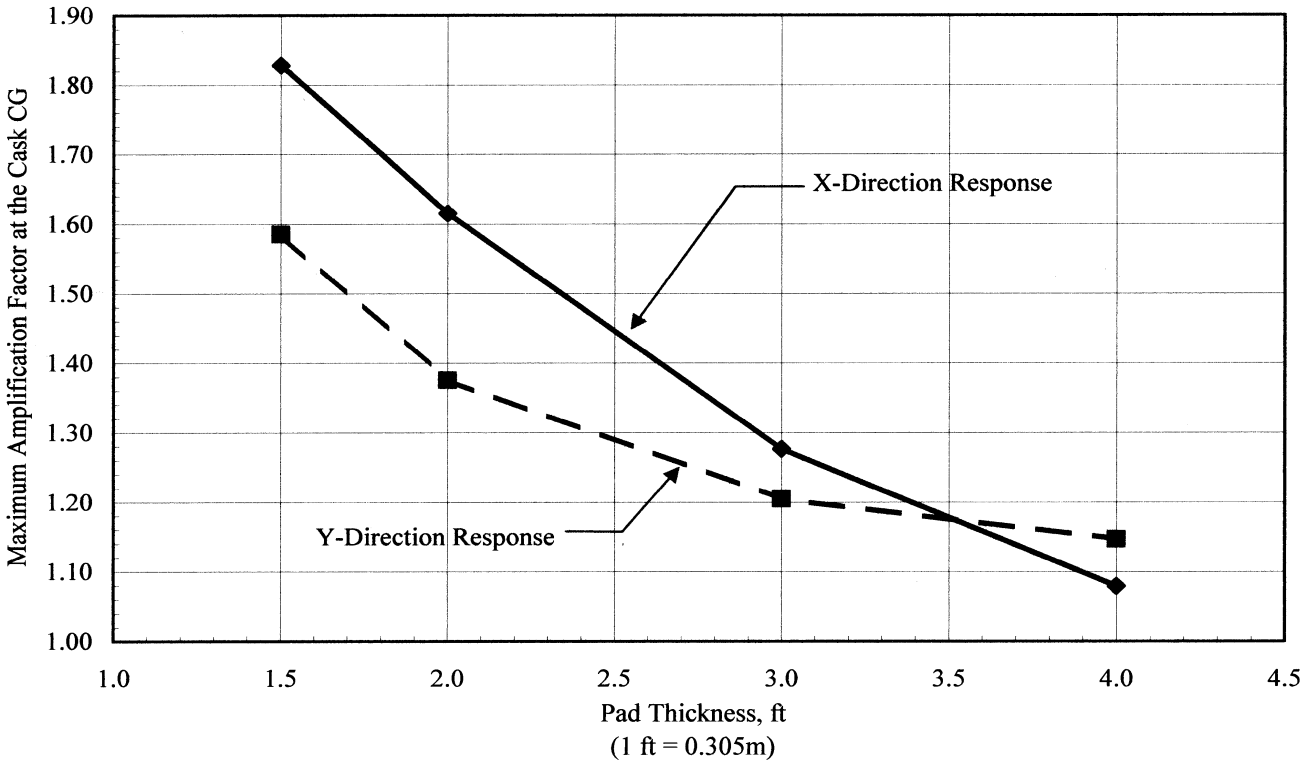

Figure 5: Amplification Factor vs. Pad Thickness for the 3-Cask Case for a Shear Wave Velocity of 1100 fps

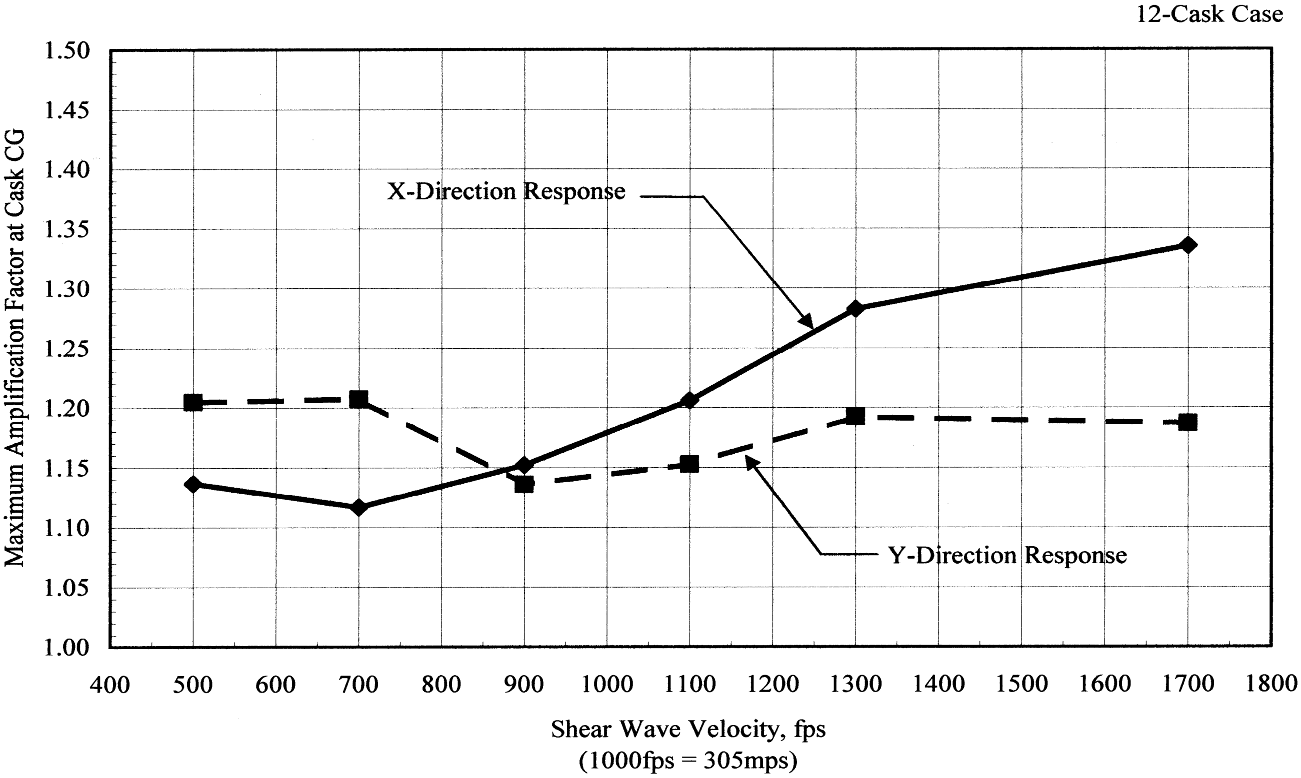

Figure 6: Amplification Factor vs. Shear Wave Velocity for the 12-Cask Case for a 2 foot Thick Pad

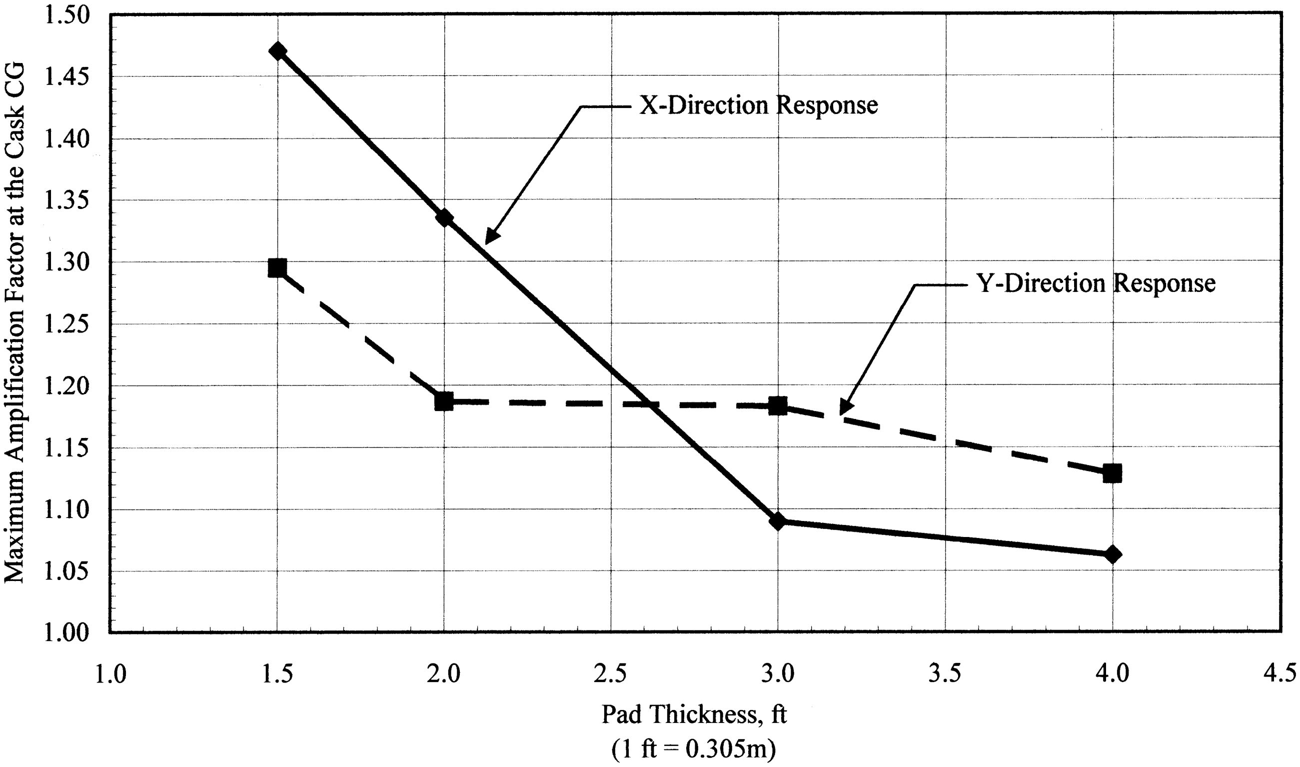

Figure 7: Amplification Factor vs. Pad Thickness for the 12-Cask Case for a Shear Wave Velocity of 1100 fps

The greater negative interaction at lower shear wave velocity reduces overall cask response, resulting in higher response at higher shear wave velocity where negative interaction is less. As increasing shear wave velocities shift the frequency of the system even higher, and out of the amplified region of the ground spectrum, cask response will no longer increase.

For the 12-cask case with a soil profile having a shear wave velocity of 1700 fps (518mps), Figure 7 once again shows the dramatic change in cask response resulting from changes in pad thickness. Unlike the 3-cask case, there is no single cask or pair of casks that produces maximum response, although generally the casks closer to the center of the pad, away from the stiffer foundation at the ends, produce the largest response.

SUMMARY OF OBSERVATIONS AND CONCLUSIONS

1. ISFSI pad thickness (flexibility) is the dominant factor influencing cask response (See Figures 5 and 7). Only when pad thickness reaches 4 feet (1.22m) and greater does the pad approach a rigid condition.
2. The second largest contributor to cask response is the partial arrangement of casks on the pad. Going from the 12-cask case to the 3-cask case, the maximum amplification factor for a 2 ft (0.61m) thick pad increased by 34% (See Table 1).
3. As expected, shear wave velocity influences maximum cask response, although not as significantly as pad thickness and cask arrangement. In general, SSI analysis at a specific site will not consider the range of shear wave velocities considered here, and thus the overall influence of soil properties would be expected to be less.
4. The maximum amplification factor at the CG of any cask is 1.83 and occurs for the 3-cask case. [This maximum amplification factor must be viewed in connection with the maximum amplification factor of the ground response spectrum, which is 2.12. Had a ground spectrum with a higher amplified region been used, such as an 84% NEP spectrum instead of a median centered spectrum, higher amplification would have occurred, since the fundamental frequency of the cask/pad/soil system was generally within the amplified region of the ground spectrum.]
5. The maximum amplification factor at the base (top of pad) of any cask is 1.05 and occurs for the 12-cask case.
6. Coupling among responses in the three orthogonal directions contributes negligibly to the overall response in each component direction.
7. Maximum response is dominated by ground motion input in the short (X) direction of the pad.
8. In the 3-cask case, the isolated cask (cask 10) always produces higher response at the CG than the closer spaced double casks (casks 2 and 3), although not significantly higher.
9. The results indicate that the more isolated a cask the higher it's potential response. The single isolated cask in the 3-cask case produces the highest response, and the twelve casks in the 12-cask case produce the lowest response. The double casks (casks 2 and 3) in the 3-cask case produce response between these two extremes. This result can be attributed to the degree to which casks interact. Based on these results, it is unlikely that any other combination of casks, consistent with a loading sequence that minimizes soil settlement, could produce significantly higher response than the 3-cask case, except perhaps for a single isolated cask at one end of the pad, which should probably be avoided.

Of all the observations, the most significant is that the response acceleration at the CG of the cask is significantly higher that at the base of the cask. This finding is not consistent with the implied assumption of a rigid pad (i.e., no out-of-plane flexibility), which forms the basis for many cask seismic stability requirements. The issue of ISFSI pad flexibility and its influence in amplifying cask response is not limited to soil sites. Rock sites must also address the issue, since the relative stiffness of crushed stone and gravel layers beneath the pad do not eliminate the out-of-plane flexibility of the pad, and therefore need to be evaluated.

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