# EXAMINING OPPOSING REQUIREMENTS FOR ISFSI PADS WHEN EVALUATING CASK TIP-OVER

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## ABSTRACT

The reinforced concrete pad for an Independent Spent Fuel Storage Installation (ISFSI) for the storage of spent nuclear fuel, presents some unique analysis and design challenges for the owners and operators of commercial nuclear power plants (NPP) in the US. Several of the design requirements pose a delicate engineering balance between the strength and flexibility requirements. The United States Nuclear Regulatory Commission (US NRC) licensed storage casks are massive steel or concrete structures weighing anywhere from 60 to 200 tons. The NRC considers that cask tip-over should be analyzed for applicable design loads resulting from natural phenomena events. In the absence of an identified hazard the NRC has accepted a non-mechanistic cask tip-over event. The large weight of these casks makes it necessary to design a strong storage pad. However, the pad also needs to be sufficiently flexible to minimize "g" loads on the cask and contents in the event of cask tip-over.

This balance is achieved by optimally engineering the sub-surface foundation materials and pad to achieve the required strength and flexibility. The regulatory requirements for adequacy of the pad design are addressed in the 10 CFR Part72. Other guidance documents are: NRC Regulatory Guide (RG) 3.73, Standard Review Plans NUREG-1536 and NUREG-1567, and Interim Staff Guidance (ISG) documents as applicable. The site-specific environmental conditions and natural phenomena load may or may not govern the design of the pad. ***However, in all cases tip-over needs to be addressed***. This paper briefly examines the opposing requirements for the pad design to withstand cask tip-over, and address the challenges in meeting these requirements.

## 1. INTRODUCTION

There are approximately 102 nuclear power plants operating in the United States (US). Most of the nuclear spent fuel is now being stored in the high-density "wet" spent fuel pools adjacent to reactors. As pools begin to approach their storage limits, independent spent fuel storage installations (ISFSIs) are being built at the existing nuclear power plant sites, and a few away from the reactor site, to accommodate the growing inventory of spent fuel.

In the US the ISFSIs licensed (and those that will be built in future) store the spent fuel in dry casks approved for this purpose by the United States Nuclear Regulatory Commission (NRC). These storage casks are normally placed on reinforced concrete pads within the secure perimeter of the power plant site. These casks are inherently passive and safe, as they are structurally robust, and cooled by natural circulation of air. These casks have to withstand natural phenomena hazards such as tornado, high wind, flood, earthquake, tsunami, etc., among other loads. Spent nuclear fuel storage casks and systems must be designed to meet four safety objectives: a) ensure that doses from spent fuel in the casks and systems are less than limits prescribed in the regulations, b) maintain sub-criticality under all conditions, c) ensure the integrity of confinement boundary under all credible conditions of storage, and d) allow retrieval of the spent fuel from the storage systems. Loads and loading conditions for Normal, Off-normal, and Accident conditions need to be in compliance with requirements of 10 CFR Part 72 [1]. The NRC approved dry cask storage systems (DCSS) are either vertical modules, or horizontal modules, made of steel, concrete and combinations of these and other materials. Typical dry cask storage system is shown in Figure - 1.

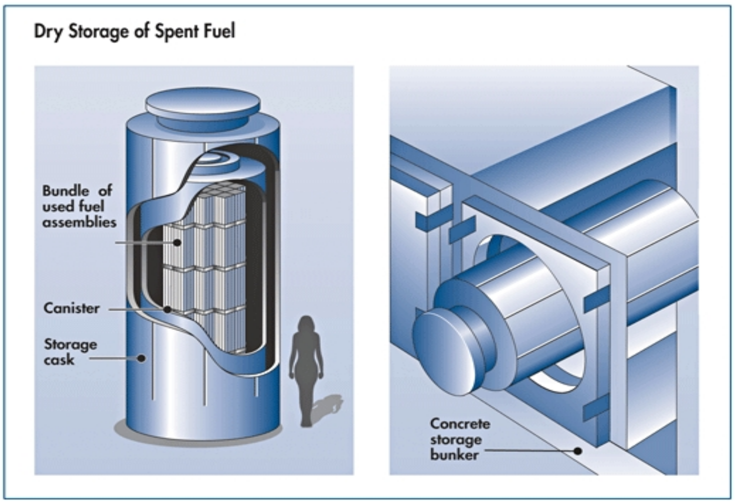


**Figure - 1 Typical DCSS**

## 2.0 STRUCTURAL DESIGN OF STORAGE PAD

This paper will discuss the issues related to the structural design of the storage pad for an ISFSI structure. Current NRC regulations (based on prescriptive requirements) for design and construction of ISFSIs are evolving to become more risk-informed. Performance based specifications and requirements are yet not available for these types of structures. Some of the loads under normal, off-normal and accident conditions for verifying adequacy of structural design are as follows:

Handling Accident and Tip Over, Snow/Ice, Flood, Tsunami, High Winds, Tornado, Tornado Missiles, Earthquakes, etc.

The regulatory licensing requirements for ISFSIs are governed by 10 CFR Part 72 [1] Regulatory Guide 1.76 [2], Regulatory Guide 3.73 [3], NUREG-1536 [4], NUREG-1567 [5], and applicable Interim Staff Guidance are among the guidance provided for the storage and design of ISFSIs. The requirements per regulations have to be met, as a minimum. A storage pad loaded with several of the vertical dry casks is shown in Figure - 2 below.

**Figure - 2 Typical Dry Cask Storage Pad**

## 3.0 HANDLIG ACCIDENT, TIP-OVER AND DESIGN OF PAD

Handling loads occur during the movement and placement of the cask on the pad or the insertion of the Multi-purpose Canister (MPC) into the storage over-pack. Handling accidents such as: drop, are considered credible events and must be evaluated. The stress analysis assume that the inertial loading on the load bearing members of the MPC, fuel basket, and the over-pack due to a handling accident are limited by certain decelerations. The product of the rigid body deceleration sustained by the structure and the dynamic load factor (DLF) applicable to that particular structural component determines the overall maximum deceleration experienced by that component. However, the rigid body deceleration is a strong function of several factors such as: the load-deformation characteristics of the impact interface, weight of the cask, and the drop height or angle of free rotation. As the weight of the structure and its surface compliance characteristics are known, the only unknown is the contact stiffness of the ISFSI pad. This unknown is a site-dependent factor, and varies from site to site, pad to pad. Therefore, it is required of an applicant to demonstrate that the rigid body decelerations experienced by the DCSS during a handling accident or non-mechanistic tip-over are below the design basis decelerations. This paper will specifically address the tip-over event as it pertains to design of the reinforced concrete pad.

The storage pad capacity requirements are established based on the load it will sustain for the design life. The sub-grade provides the foundation for supporting the pad and base courses. That is why the performance of the pad depends on uniformity and bearing capacity of the sub-grade.

Generally, when performance of the rigid floor slab is unknown, the modulus of sub-grade reaction "k" to be used for the design purposes is determined by the field plate-bearing test. Usually adequately accurate values for "k" can be estimated based on the site-specific soil type, drainage and frost conditions. Tables are available for most types of materials. These values are increased slightly but never to exceed a value of 135 Mpa (500 pounds per cubic inch), if the density is greater than 95 % maximum CE density. In most instances a field plate bearing test is conducted to determine more accurate value based on particular site conditions.

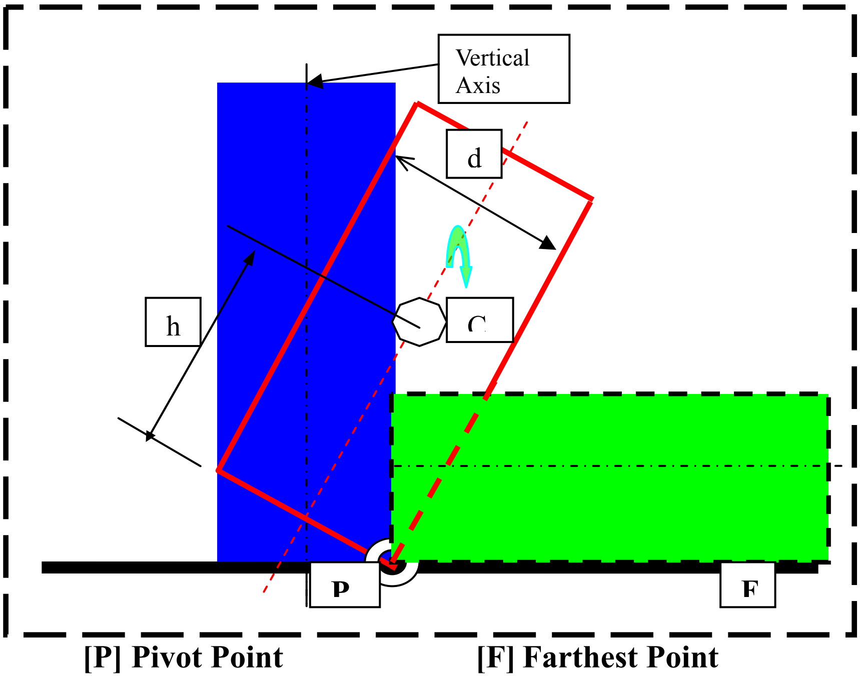


**Figure - 3 Tip-Over Condition**

For the tip-over analysis, a loaded cask is assumed to undergo a non-mechanistic tip-over event impacting the ISFSI pad with an incipient angular velocity. Figure-3 above depicts the free body diagram of the tip-over condition:

The Lawrence Livermore National Laboratory (LLNL) published the experimental results from the fourth series billet steel tests [8] documenting numerical solution in a report [9] which simulated the drop test results. U. S. NRC has reviewed and endorsed the LLNL methodology [10]. The LLNL simulation method used same modeling and simulation algorithms as those used in the commercial computer code DYNA3D [11].

The reinforced concrete supporting pad is typically 0.915m (36") thick, and is usually placed on top of the engineered fill, which varies depending on the substrata at a specific site. Principal design goal when designing the pad is to ensure that the pad and its underlying foundation are sufficiently strong to withstand the considerable dead weight of the casks and that the foundation will not subject to liquefaction under the specific site's Design Basis Earthquake (DBE) event. Note that the layer of engineered fill is basically used to provide "softness" to the foundation. This is to ensure that the pad satisfies the tip-over "g" load criteria (typically in the range of 45g to 60g) as prescribed in the Certificate of Compliance (CoC) for that particular (vendor supplied) cask. This is where the opposite design requirements has to be dealt with and extra precaution has to be taken to balance and satisfy both the requirements. *The pad has to be "strong enough" to carry weight, at the same time "soft enough" to accommodate the maximum deceleration in a postulated non-mechanistic tip-over.*

We will discuss this issue further. One could argue that the tip-over requirement is quite clearly at odds with the strength and overall robustness required for the pad to sustain extremely heavy loads from the cask. The cask (or the over-pack) is assumed to be perched on its edge with its Center of Gravity (CG.) directly over the pivot point P (Figure-3). With zero initial velocity the cask (or the over-pack) begins its downward rotation. At the end of the tip-over event, the cask (or the over-pack) is horizontal. At this instant the downward velocity is ranging from zero at the pivot point P to a maximum velocity at the farthest point of impact F. What needs to be demonstrated using the commercial code such as DYNA3D [11] mentioned above (or equivalent other methods), that the maximum rigid body deceleration of the cask centerline at the plane of the top of the fuel basket cellular region is less than the decelerations prescribed in the relevant CoC.

## 4.0 FACTORS AFFECTING STRUCTURAL DESIGN OF PAD

The flexural strength of the reinforced concrete rigid pad for the ISFSI is very important to its design. The design is based on the strength of the pad, which distributes loads uniformly to the sub-grade under the pad. One of the most difficult (yet, very important) soil parameters is the modulus of the soil (also known as coefficient or modulus of sub-grade reaction "k"). As we need to satisfy two opposing requirements discussed above, it is very important to ensure that the as-built in-situ sub-grade under the ISFSI pad is capable to render the required strength as well as softness to the pad.

To obtain a modulus from a stress strain curve normally a tri-axial test is performed in the laboratory on a soil sample (cylinder) taken from the in-situ soil. The sample is wrapped in an impervious membrane and confined by an all around pressure. Then the vertical stress is increased gradually and the non-linear stress strain curve is obtained. In this test it is necessary to measure the stresses applied, and strains induced in both directions in order to calculate the sub-grade modulus. Soils do not exhibit a linear stress strain curve, and one needs to be careful in defining the modulus from results of a tri-axial test. A secant modulus E (also known as elastic modulus or Young's modulus after Thomas Young who published the concept back in 1807) is used to predict the movement due to the first application of the load on spread footing (typical for ISFSI pad). The modulus E has units of force per unit area e.g. $kN/m^2$ (psi).

**Figure - 4 Field Plate Bearing Test**

Elastic modulus represents a constant ratio of stress over strain (stiffness). There is no direct laboratory procedure for determining "k" value. Figure 4 shows a typical field plate bearing test to determine *in-situ* modulus of sub-grade reaction "k". The modulus of sub-grade reaction came about mainly due to work done by Westergaard during the 1920s. The value "k" was developed to be used as a spring constant to model the support beneath the pavement slab. Almost all materials (including the sub-soil) are elastic to some degree as long as the applied load does not cause a permanent deformation. Thus "flexibility" of structure depends on its elastic modulus and geometric shape. It should be noted that measure of a material's modulus of elasticity is not a measure of *strength.* Strength is the stress needed to break or rupture a material. Therefore it is important to remember that the *modulus of sub-grade reaction is not a soil property and it depends on the size of the loaded area*. The value of "k" derived in this manner is always site-specific. If P = applied pressure (load divided by the area of the test plate) then, $P = k\Delta$ or

$$\mathbf{k = P / \Delta} \qquad \text{(Eq. 1)}$$

Where, $\Delta$ = measured deflection of the test plate

The modulus of sub-grade reaction "k" is defined here as the ratio of the pressure applied to the boundary through a loading area divided by the displacement experienced by the loaded area. It has units of force per unit volume i.e. $kN/m^3$ (pci). The standard such as ASTM D 1196 [12] describes a general procedure for standard plate bearing test used to determine the "k" value. ACI 360R [13] also provides detailed information on similar test, using various diameter test plates. The value "k" for sub-soil conditions for ISFSI site using NRC approved cask, needs to be such that it will satisfy the "g" load criteria for the tip-over condition as prescribed in CoC for that particular cask.

The Division of Spent Fuel storage and Transportation at the U. S. NRC office has noted that lately, number of applications for ISFSI construction have been docketed (in cases where the original existing soil condition were not optimum) for NRC's approval to satisfy this requirement. In some cases the soil stabilization was done to minimize potential of liquefaction and/or settlement where the in-situ soil sub-grade was "strengthened" or "stabilized" by mixing soil with concrete mix. If a high-quality, well-compacted granular sub-base is used under the ISFSI pad, "k" value can be increased to meet this "g" load criteria. Sometimes a layer of granular material is placed on top of the prepared sub-grade which can provide benefits during the construction process and afterwards. This thin layer of granular material on top of the prepared sub-grade provides a cushion for more uniform distribution of load by equalizing minor sub-grade defects. Table-1 illustrates how the balance between strength and flexibility was achieved at ISFSI pads built at a commercial nuclear power plant.

**Table – 1***

| **Soil Parameter** | **"Before" Soil Stabilization (Untreated Soil)** | **"After" Soil Stabilization (Treated Soil)** |
|---|---|---|
| Minimum Compressive Strength of Soil Elements | N/A | 1.10 MPa (160 psi) |
| Young's Modulus Ave. Upper 45'<br>Upper 75'<br>soil-cement elements only | 10 MPa (1.45 ksi)<br>2.53 MPa (3.67 ksi)<br>N/A | 194 MPa (28.2 ksi)<br>137 MPa (19.9 ksi)<br>447 MPa (65.0 ksi) |
| Poisson's Ratio | 0.3 | 0.3<br>0.07 ~ 0.15 (soil-cement elements only) |
| Shear Strength | N/A | 0.56MPa (81.0 psi) |
| Soil Bearing Capacity | 0.06 MPa (1.2 ksf)<br>- based on settlement | 0.24 MPa (5.0 ksf) - underlying clay governs |
| **Sub-grade Modulus** | **0.54~2.17 $MN/m^3$**<br>**(2 ~ 8 pci)** | **8.14 $MN/m^3$**<br>**(30 pci)** |
| Estimated Settlement | 0.10 ~ 0.20m (4"~ 8") | 0.01m (0.5") |
| Estimated Liquefaction Potential<br>1.80m ~ 7.62m (6' ~ 25')<br>depth was susceptible | 30%<br>(questionable) | ~ 0% |
| Seismic Response at Top of Pad (Max.) | NS = 0.26g, EW = 0.26g | NS = 0.32g, EW = 0.36g |

| | | |
|---|---|---|
| | | |

*Courtesy PSEG

Table-1 shows considerable difference in the basic soil parameters prior to and after soil stabilization. The most remarkable difference that can be observed is that the potential for liquefaction estimated at 30%, was almost eliminated after stabilization. Also, the sub-grade modulus of the soil underneath the reinforced concrete pad was strengthened from approximately Ave. 1.36 $MN/m^3$ (5pci) to 8.14 $MN/m^3$ (30 pci). The overall soil bearing capacity was strengthened by almost four times. The maximum seismic response was increased by approximately 27% in EW direction, and approximately 38% in NS direction.

An ISFSI applicant may choose to strengthen the existing soil underneath the concrete pad supporting the DCSS by various methods. As can be seen in Table -1 above, in-situ soil stabilization has significant effects not only on the dynamic response of the structure under design basis seismic event, but it also helps in achieving the required soil sub-grade modulus to meet the tip-over "g" load criteria requirements prescribed in the CoC.

## 5.0 CONCLUSIONS

Structures, Systems, and Components (SSCs) classified as important to safety are designed to withstand the effects of site-specific environmental conditions and natural phenomena such as earthquake, tornado, flood, etc. The design of supporting reinforced concrete pad for storage of spent nuclear fuel, presents some unique analysis and design challenges. As a uniform rather than strong support is the most important function of the sub-grade for an ISFSI pad, it is paramount that pad strength is achieved by building required strength into the reinforced concrete pad itself, with proper mix of soil sub-grade materials under the pad. The potential for long-term consolidation settlements under sustained heavy loads should be carefully evaluated. Needless to say that inspection and testing of controlled fills are extremely important to ensure uniformity of support. This paper has addressed some of these challenges related to pad design and the balance that must be achieved simultaneously satisfying strength and flexibility requirements. Other issues may evolve in the future. The four safety goals mentioned above are to be met under all conditions.

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