SEISMIC SLOPE STABILITY AND DESIGN/ANALYSIS OF AN INDEPENDENT SPENT FUEL STORAGE INSTALLATION (ISFSI) PADS

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ABSTRACT

The regulatory requirements for analysis and design for structures, systems, and components (SSCs) related to independent spent fuel storage installations (ISFSIs) in the United States of America (USA) are identified in 10 CFR Part 72. Applicable guidance documents include: the United States Nuclear Regulatory Commission (US NRC) Regulatory Guide (RG) 3.73; Standard Review Plans NUREG-1536 and NUREG-1567; and NRC Division of Spent Fuel Storage and Transportation Interim Staff Guidance (ISG) documents. Utilities owning and operating commercial nuclear power plants (NPPs) may choose to build an ISFSI that is co-located at the existing plant site, or may choose to transfer the spent nuclear fuel to an off-site facility, if available. An important design consideration for an ISFSI involves the specific site soil conditions, which may vary considerably from one site to another.

The ISFSI reinforced concrete pads are designed to withstand the effects of site-specific environmental conditions and natural phenomena, such as earthquakes, tornadoes, and floods. Required analyses for such phenomena include the evaluation of the wave propagation characteristics of subsurface materials with interaction effects of structures; analysis of the potential for soil liquefaction; settlement under dynamic loading; and analysis and effects of earthquake loading and the stability of slopes and embankments. These phenomena may affect spent fuel cask system performance, if the integrity of the reinforced concrete foundation pad is jeopardized, or if the casks themselves are directly impacted. This paper will briefly address the issues and challenges encountered when considering the stability of nearby slopes under static as well as site-specific seismic (dynamic) loading conditions.

1. INTRODUCTION

There are approximately 102 nuclear power plants operating in the USA. Most commercial spent nuclear fuel is now being stored “wet,” in high or low-density storage racks in spent fuel pools adjacent to reactors. As spent fuel pools begin to approach their storage limits, ISFSIs are being built at existing nuclear power plant sites and at a few away-from-reactor sites, to accommodate the growing inventory of spent fuel. In the USA, ISFSIs at reactor sites are authorized to store the spent fuel in dry casks approved for this purpose by US NRC. Typically, these storage casks are placed on reinforced concrete pads within a secured, protected area on the power plant site.

Spent nuclear fuel storage casks and systems must be designed to meet four safety objectives: 1) maintain doses from the stored spent fuel below the limits prescribed in the regulations; 2) maintain the spent fuel sub-critical under all conditions; 3) maintain the integrity of confinement boundary under all conditions; and 4) 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]. ISFSIs across the nation have spent nuclear fuel stored in dry cask storage systems (DCSS) that have been approved by NRC for an initial term of 20 years, which may be renewed upon reapplication and subsequent approval by NRC. These cask systems are inherently passive and safe, as they are structurally robust; and the spent fuel in storage is adequately cooled by natural circulation of air between the outer cask and inner, sealed canister. These dry cask storage systems also have to withstand natural phenomena such as

tornadoes, floods, earthquakes, tsunami, etc., in addition to other loads. A typical DCSS, with vertical storage modules (casks) on a reinforced concrete pad, is shown in Figure 1.

Figure 1: Typical Vertical DCSS on Pad at a Nuclear Power Plant

2.0 SITE-SPECIFIC ISSUES

This paper will discuss some of the site-specific issues related to the structural design and analysis of an ISFSI, focusing on the stability of slopes during a design basis seismic event. NRC regulations for design and construction of ISFSIs are evolving to become more risk-informed. However, performance-based specifications and requirements have not yet been developed for these types of structures.

In verifying the adequacy of the structural design of an ISFSI, various loads must be considered, including those associated with the following normal, off-normal and accident conditions:

- Handling Accident and Tip Over, Pressure, Temperature and Solar Radiation,
- Blockage of Vent Ducts, Snow and Ice, Flood, Tsunami, High Winds, Tornado, Tornado Missiles, Earthquakes, Slope Stability

NRC-approved dry cask storage systems employ vertical or horizontal storage modules, made of steel, concrete or combinations of these and other materials. A typical horizontal system stored on a concrete pad is shown in Figure 2.

Figure 2: Typical Horizontal DCSS

The regulatory requirements for the design of licensing of ISFSIs and DCSSs are identified in 10 CFR Part 72 [1]. Applicable guidance documents include: US NRC Regulatory Guide 3.73 [2], NUREG-1536 [3], NUREG-1567 [4] and Interim Staff Guidance. The discussion that follows will briefly address various design loads, and will focus in greater detail on the issue of stability of slopes.

3.0 LOADS OTHER THAN SEISMIC

For most typical DCSS designs, the spent fuel is loaded into an inner canister, while still under water in the spent fuel pool. The loaded canister is lifted out of the spent fuel pool in a shielded transfer cask and the entire assembly is placed in a location within the fuel handling building, where the canister can be dried, filled with an inert gas, seal welded and leak tested. Following these canister preparation activities, the canister is transferred to a storage cask or overpack, which is in turn, transported to the ISFSI pad and placed in its storage location. In some cases, the loaded canister is moved to the ISFSI pad inside the transfer cask, and is subsequently transferred to the storage overpack or module at or near the ISFSI.

Therefore, handling loads may be imparted on the canister and/or the storage module or overpack during transfer or emplacement activities. The guidance provided in Reg. Guide 3.61 [5] for cask lifting operations may be applicable to these evolutions. The load factor for internal moments and forces caused by temperature distributions within the concrete structure that occurs due to normal operating or off-normal conditions must be considered, and is specified by ACI 349-01 [6] as 1.05. NRC Reg. Guide 1.142 [7] recommends a factor of 1.2, and NUREG-1536 [3] suggests using a factor of 1.275, to be used in load combinations when tornado loads are combined with dead load, live load, and loads due to the weight and pressure of soil, water in soil, or other materials.

The site-specific historic daily, historic monthly, and the average annual snowfall, published records of ice storms in the area where ISFSI is planned, etc. must also be considered. Long-term accumulation of snow and ice may lead to undesirable freezing of the soil in the nearby surroundings and could create conditions that must be evaluated. The surface topography and hydrology around the ISFSI area and the relation to the existing drainage system need to be thoroughly evaluated to ensure that flooding of ISFSI structures will not occur. The elevation of the ISFSI relative to other existing structures nearby will help determine if there exists any potential of inundation due to a design basis flood.

A typical tsunami wave has a very long wavelength when it comes ashore, like a long lasting flood wave, rather than the breaking surf we commonly see at the beaches. The potential effects of such flooding on an ISFSI must be addressed. The top elevation of the ISFSI cavity (vault) with respect to mean sea level elevation, bounding estimates for distant tsunamis, as well as locally generated tsunamis associated with various seismic zones based on historical and potential earthquakes need to be considered. The ISFSI design must ensure that the damaging tsunami wave forces cannot lift the entire structure and put the structure in an unanalyzed condition. The ISFSI concrete structures could be vulnerable to the flowing waters and water-borne debris created by tsunami waves. The entire soil and sub-soil supporting the base mat could degrade from tsunami forces and must be considered when evaluating the stability of the ISFSI.

4.0 STABILITY OF SLOPES AND DESIGN BASIS SEISMIC EVENT

NRC Regulatory Guide 3.73 [2] identifies design earthquake motions to be considered for nuclear safety-related structures. Other applicable references for the analysis of this design basis

event are ANSI/ANS [8] and ASCE standards [9]. It is incumbent upon the ISFSI licensee to ensure that site-specific licensing basis loads are appropriately addressed; and that the methods used for combining the effective loads are in accordance with NUREG-0800 [10], and are consistent with the defense-in-depth approach. In addition to the vibratory ground motions associated with design basis earthquake event, the design analysis of an ISFSI structure must consider seismically induced effects; e.g., soil erosion, slope instability, liquefaction, subsoil compression and related short-term and long-term settlement, and inundation. NRC Regulatory Guide 3.73 [2] suggests that a Probabilistic Seismic Hazard Analysis (PSHA) should be performed to systematically take into account uncertainties and alternative hypotheses. These uncertainties are in the form of both aleatory, and epistemic uncertainty. Aleatory uncertainty leads to the shape of the hazard curve, and epistemic uncertainty leads to alternative hazard curves. The source models, ground motion attenuations, and the site response models should be consistent with the Senior Seismic Hazard Analysis Committee (SSHAC) [11] guidelines.

Seismically-triggered sudden failure of slopes located near an ISFSI pad with a DCSS (typically unanchored) can result in transport of debris down hill, landing directly on the pad. The debris can be transported on to the pad by slumping, falling, sliding, or mixed with water or air as sediment. The shape and location of the failure is unknown, but initial assumptions are used with an iterative approach to define the minimum factor of safety. Slope stability analysis is broadly categorized in either infinite slope analysis, or a finite slope analysis. In an infinite slope analysis, the failure is translational along a single plane failure surface parallel to slope surface. This type of analysis is typically applicable for surface raveling in granular materials or when a concrete slab slides in cohesive material.

A finite slope analysis can be for a failure surface that is plane, circular, or non-circular. In a plane failure, the translational block slides along a single plane of weakness (or a geological interface). The guidance provided in the RG 3.73 [2] calls for the analysis of the casks and the ISFSI structure to use the spectra and time histories in the three orthogonal directions. For the geotechnical analysis, the vertical ground motions may have the greatest influence the seismic induced displacements. Depending upon the magnitude of the peak ground acceleration at a specific site, this may have to be included in the deformation analysis using pseudo-static analysis, or the Newmark stick-slip sliding block analysis [12] that was developed in 1965, which is still generally followed to calculate seismically-induced displacement on slopes. The potential sliding mass on a slope during an earthquake is simplified to a block (with weight W) sliding on a horizontally moving plane**.** The block will "stick" to the foundation and they will tend to move together when the inertial force on the block induced by the excitation (due to earthquake) from the moving foundation plane is less than the frictional resistance between the block and the foundation. During strong ground shaking with high acceleration, the inertial force on the block exceeds the frictional resistance between the block and its foundation, and the foundation will accelerate away from the block. There are number of complexities involved in understanding the actual wave propagation through a 3-D geologic structure. The increased vertical load on the reinforced concrete pad underneath the storage cask from a downward directed vertical seismic acceleration could affect the structural integrity of the ISFSI. For further elaboration and issues related to this method refer to Reference [13].

Most textbooks on soil mechanics include several methods of slope stability analysis. Methods currently used to calculate the factor of safety of a potential circular failure surface include: the ordinary method of slices also known as Fellenius' method; Bishop's simplified or modified method; and Spencer's method. For non-circular failure surface analysis, methods include: the wedge method or force equilibrium method; Janbu's simplified method; and Morgenstern-Price's method. Relative merits and applicability of these methods are well covered in modern text books. Detailed guidance for various methods of slope stability analysis is presented in, "Slope Stability and Stabilization", by Abramson, et al. [14].

Bishop's simplified or modified method is a rigorous method solved using a computer algorithm, and is typically used for circular failure surfaces in any type of soil. It uses the method of slices and limit equilibrium. Limit equilibrium analyses are based on the upper bound theorem. In the method of slices, the soil mass lying before the trial failure is divided, by vertical planes, into a series of slices of equal width. Several possible failure surfaces are considered, until the least favorable is found. The factor of safety is determined for the least favorable surface. Before slope stability can be calculated using these methods, some assumptions, for example, the side forces and their directions have to be predicted in order to build the equations of equilibrium. These methods require strength information of the soils. In general, these methods require the soil mass to be divided into slices. The directions of the forces acting on each slice in the slope are assumed. This assumption is a key role in distinguishing one limit equilibrium method from another. Limit equilibrium methods require that a continuous surface passes the soil mass. This surface is essential in calculating the minimum factor of safety against sliding or shear failure. These methods do not provide information about the magnitude of movements. However, they yield a factor of safety that is usually applied in the design processes. Figure 3 shows a typical circular failure phenomenon.

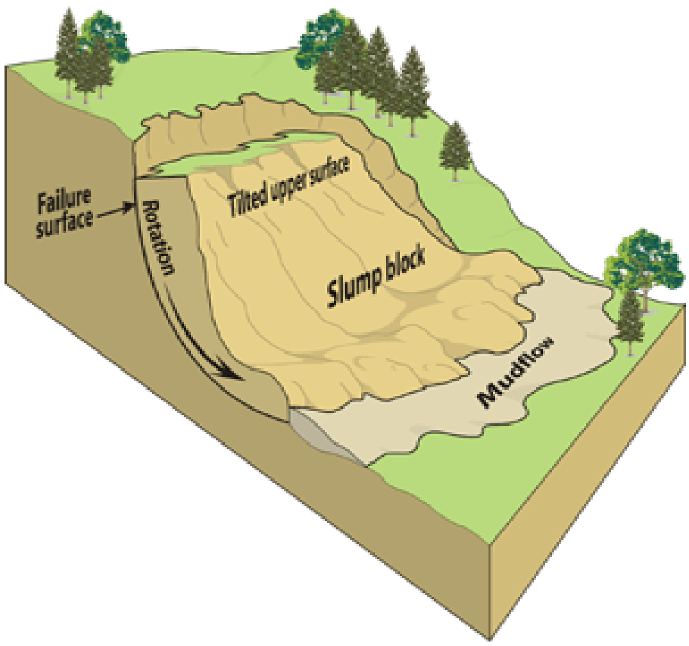

Figure 3: Circular Failure Surface

Lately finite element methods such as SLOPE/W [15] and others have been increasingly used in slope stability analysis. The advantage of a finite element approach in the analysis of slope stability problems over traditional limit equilibrium methods is that no assumption needs to be made in advance about the shape or location of the failure surface, slice side forces and their directions. The method can be applied with complex slope configurations and soil deposits in two or three dimensions to model virtually all types of mechanisms. The equilibrium stresses, strains, and the associated shear strengths in the soil mass can be computed very accurately. The critical failure mechanism developed can be extremely general and need not be simple circular or logarithmic spiral arcs. The method can be extended to account for seismically induced slope failure and various other parameters.

Generally, there are two approaches to analyze slope stability using a finite element method. One approach is to increase the gravity load and the second approach is to reduce the strength characteristics of the soil mass. Modern methods take the approach of adjusting the soil shear strength parameters such as cohesion, or the tangent of the internal angle of friction, etc., until the resisting and mobilizing moments are equal. The adjustment ratio applied to these strength

parameters is then essentially the factor of safety. Important aspects in slope stability analysis are: the material properties of the slope model, the influence of calculating factor of safety to slope stability, and the definition of the slope failure. Slopes fail because the material shear strength on the sliding surface is insufficient to resist the actual shear stresses. Factor of safety is a value that is used to examine the stability state of slopes. Factor of safety values greater than 1 mean the slope is stable, while values equal to and lower than 1 mean the slope is unstable. In relation to the shear failure, the factor of safety against slope failure is simply calculated as:

$$\textbf{Factor of Safety} = \frac{\text{Shear Strength of Slope Material}}{\text{Mobilized Shear Resistance of Sliding Surface}}$$

This method has been referred to as the "shear strength reduction method." To achieve the correct strength reduction factor, it is essential to trace the value of factor of safety that will just cause the slope to fail. Non-convergence within a user-specified number of iterations in a finite element program is taken as a suitable indicator of slope failure. This actually means that no stress distribution can be achieved to satisfy both the Mohr-Coulomb criterion and global equilibrium. Slope failure and numerical non-convergence take place at the same time and are joined by an increase in the displacements. Usually, the value of the maximum nodal displacement just after slope failure indicates a big jump compared to the one before failure [16**]**

Figure 4: Effects of Unstable Soil Slope

When the slope failure mechanism is not accurately modeled by limit equilibrium techniques, more sophisticated analysis, such as finite difference methodology like the one used in the FLAC computer program may be used in addition to the limit equilibrium methods to validate the results of the traditional techniques. If the results from the two methods are significantly different, engineering judgment needs to be applied to evaluate the appropriateness of the design model used.

When the slope heights are in the range of 15 to 20 feet or higher, the potential slope failure mechanism is relatively shallow and parallel to the slope face. In such cases, infinite slope analysis should be conducted. If the soil mass is cohesion-less (e.g. dry sand), and is either fully submerged, or located above the site-specific water table, the factor of safety is calculated by:

$$\text{Factor of Safety} = \frac{\text{Tan } \Phi}{\text{Tan } \beta} \qquad \text{where,}$$

Φ = the angle of internal friction of soil

β = the slope angle relative to the horizontal

If the factor of safety calculated by using the infinite slope method is in the range of 1.0 to 1.15, an unacceptable level of erosion or shallow slumping could occur. The NRC Standard Review Plan (SRP) - NUREG-0800 [17] Draft Revision 3, dated April 1996, Section 2.5.5. "Stability of Slopes," subsection 2.5.5.2, states that, "......the discussion of design criteria and analyses is acceptable if the criteria for stability of all Seismic Category I slopes are described and valid static and dynamic analyses have been presented to demonstrate that there is an adequate margin of safety." Subsection 2.5.5.2 also states, "No single method of analysis is entirely acceptable for all stability assessments; thus no single method of analysis can be recommended. Relevant manuals issued by public agencies (such as U.S. Navy department, U. S. Army Corps of Engineers, and U. S. Bureau of Reclamation) are often used to ascertain whether the analyses performed by the applicant are reasonable." Figure 4 shows the aftermath of an unstable slope when it fails.

The Department of the Navy, "Soil Mechanics, Foundations, and Earth Structures," NAVFAC DM-7.01, March 1971, Chapter 7, Section 3.g (4) - Required Safety Factor, states that, "For transient loads, such as earthquake, safety factors as low as 1.2 or 1.15 may be tolerated." The Naval Facilities Engineering Command has re-validated this requirement by Change 1 in September 1986. The commercial standards such as ANSI, ASCE, and others, also indicate that a minimum acceptable factor of safety should be 1.15 when loadings include transient loadings such as a design bases seismic event.

The acceleration values in the horizontal and vertical directions can be combined to account for the simultaneous effects of horizontal and vertical seismic excitation, and can be calculated using the 100% - 40% - 40% rule as recommended in NUREG/CR-0098 [18]. Thus, the adequacy of the ISFSI pad should be verified using slope stability analysis for two cases as follows:

Case 1: Horizontal = high (g) and Vertical = low (g)

Case 2: Horizontal = low (g) and Vertical = high (g)

The weight of the as-built pad, weight of the cask system, and the in-situ soil should be appropriately considered in response to the vertical acceleration during the earthquake. The analyses should be performed for both upward and downward vertical acceleration values to obtain the critical stability condition. The circular surface that gives the lowest factor of safety and its extent from immediately outside the base of the pad into the in-situ natural soils should be ascertained. All circular arcs beneath the pad shall have a factor of safety of greater than 1.15. The soil immediately below the pad needs to be stable and the minimum factor of safety just outside of the pad shall be 1.15 against the postulated sliding soil mass loads.

Another very important consideration for these ISFSIs is potential of seismically-induced liquefaction of subsoil. The phenomenon of liquefaction is most predominant in fluvial-alluvial deposits, Aeolian sands and silts, beach sands, reclaimed land and un-compacted hydraulic fills. Criteria that are based on physical properties rather than on blow counts should be used to evaluate liquefaction or strength loss susceptibility of fine-grained soils to ensure that the ISFSI is structurally adequate and will not pose any danger.

5.0 CONCLUSIONS

Nuclear power plant structures, systems, and components classified as important to safety are designed to withstand the effects of site-specific environmental conditions and natural phenomena such as earthquakes, tornadoes, and floods. An ISFSI for storage of spent nuclear fuel, presents some unique analysis and design challenges. This paper has addressed some of the

challenges of designing a reinforced concrete pad for an ISFSI, and the issue of stability of nearby slopes. The four safety goals mentioned above are to be met under all conditions.

6.0 REFERENCES

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