20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 6, Paper 1935

Soil Remediation for Seismic Design of Independent Spent Fuel Storage Installation (ISFSI) Pad

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Keywords: ISFSI Pad, Seismic, Soil Remediation, Soil Mixing, Compaction, Grouting.

1 ABSTRACT:

Interim spent fuel storage, using a U. S. Nuclear Regulatory Commission (NRC) approved Dry Cask Storage System (DCSS) is an acceptable means of spent fuel management, until the U. S. Department of Energy accepts and stores the spent nuclear fuel in a high-level waste repository. The DCSS' for Independent Spent Fuel Storage Installation (ISFSI) are massive steel and/or concrete structures, loaded with spent nuclear fuel, and stored (in most cases unanchored) outside on reinforced concrete pads. The storage cask vendors have specific requirements for critical soil parameters under the reinforced concrete pads.

Requirements for critical soil parameters under the reinforced concrete pad foundation supporting the DCSS have to be met to ensure stability of the pad when challenged by natural phenomena such as seismic events. These requirements vary for different vendors and are described in the vendor-specific Certificate of Compliance (CoC) issued by NRC. In instances where the existing soil is vulnerable to potential liquefaction, and/or settlement because of a design-basis seismic event, various approaches could be used by licensees to stabilize the natural soil. The reinforced concrete pad foundation is required to satisfy the safety objectives of Title 10 of the Code of Federal Regulations (10 CFR) Part 72. Regulatory Guides (RGs), NUREGs, Standard Review Plans (SRPs) and other guidance documents are available to assist an applicant in complying with the regulations.

This paper will: 1) provide an overview of selected approaches that could be used for meeting the seismic demand on the storage pad for ISFSIs licensed under the provisions of 10 CFR Part 72.210; 2) discuss the design process and compare the relative merits of these approaches; 3) investigate the potential effects of soil remediation; and 4) discuss the resulting soil-structure interaction effects and the seismic input ground motions appropriate for the design of the foundation.

2 REGULATORY REQUIREMENTS: ISFSIs are licensed under 10 CFR Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste," (Reference 1). 10 CFR 72.210 grants a general license for the storage of spent fuel in an ISFSI to all holders of a 10 CFR Part 50 reactor operating license. The conditions of this general license are given in §10 CFR 72.212. 10 CFR 72.212(b) (2) (i) require the general licensee to perform written evaluations, ~~prior to~~ before use that establishes that:

> *(A) Conditions set forth in the Certificate of Compliance have been met;*
>
> *(B) Cask storage pads and areas have been designed to adequately support the static and dynamic loads of the stored casks, considering potential amplification of earthquakes through soil-structure interaction, and soil liquefaction potential or other soil instability due to vibratory ground motion; and*
>
> *(C) The requirements of § 72.104 have been met.*

Additionally, 10 CFR 72.212(b) (3) requires that a licensee review the Safety Analysis Report (SAR) referenced in the Certificate of Compliance and the related NRC Safety Evaluation Report (SER), prior to use of the general license, to determine whether or not the reactor site parameters, including analyses of earthquake intensity and tornado missiles, are enveloped by the cask design bases considered in these reports.

Note that the ISFSI pads at most sites are classified as non-safety-related and non-seismic Category I structure. However, because of the radioactivity of the fuel stored within it, the installation is licensed by NRC under the regulatory requirements of 10 CFR Part 72.

All general licensees are required to perform analyses to verify that the site chosen for the proposed ISFSI will meet the design criteria contained in the cask SAR, and the CoC for the storage system. Various NRC guidelines, such as RG, SRPs, NUREGs, NUREG/CRs, etc. are available to assist in accomplishing this. For general licensees, the specifications for the ISFSI foundation are not identified in the CoC. Conversely, for site-specific licensees the specification and requirements for that given site are clearly specified in the CoC. Also, 10 CFR Part 72 does not specifically require a three dimensional Soil Structure Interaction (SSI) analysis.

Regulatory Documents vs. Guidance Documents: Regulatory documents are documents produced by NRC (e.g. RGs, NUREGs, SRPs, etc.) that are applicable to the licensing of an ISFSI, and are guidance documents only, to assist NRC staff during the review of an ISFSI application for licensing approval. Non-regulatory documents are documents that are not produced by NRC (e.g., NUREG/CR, etc.), but that may provide insight into analyses performed as part of the licensing of past ISFSI facilities.

3. METHODS OF SOIL REMEDIATION: A few of the currently available methods for improving the existing soil to enhance the soil capacity to sustain seismic loads and minimize or eliminate liquefaction potential are listed below: Courtesy of (Baker Hayward)

1) Dynamic Compaction (Densification)
2) Vibro-Compaction (Densification)
3) Vibro-Replacement (Stone Columns - Densification)
4) Vibro-Replacement (Stone Columns / Vibro Piers - Reinforcement)
5) Drainage and Surcharge (Densification)
6) Soil Mixing/Deep Mixing, Wet (Reinforcement)
7) Soil Mixing/Deep Mixing, Dry (Reinforcement)
8) Compaction Grouting (Densification)
9) Compaction Grouting (Reinforcement)
10) Cement Fracture Grouting (Compensation)
11) Chemical Grouting Silicates (Reinforcement, Reduce Permeability)
12) Jet Grouting

Each one of these methods has its unique technical and construction issues, and the estimated cost varies from as little as $2 per 0.76 cubic meter (cubic yard) to $300 or more per 0.76cubic meter (cubic yard) depending on the complexity of the soil conditions (ground characteristics) at specific site. These cost estimates do not include any costs related to mobilization, site preparation, and demobilization. The treatment depth ranges from less than 1.5m (5ft.) to depths exceeding 30.5m (100 ft.). For deeper soil sites, ISFSI Pads supported on vertical and/or battered piles have also been used at some locations.

There are basically three possible ways to reduce liquefaction hazards when designing and constructing new structures: 1) avoid liquefaction susceptible soils 2) build liquefaction resistant structures 3) improve the soil.

The first possible way is to avoid construction on liquefaction-susceptible soils. There are various criteria to determine the liquefaction susceptibility of a soil. By characterizing the soil at a particular building site, according to these criteria, one can decide if the site is susceptible to liquefaction and therefore unsuitable for the desired structure.

Secondly, if it is necessary to construct on liquefaction-susceptible soil because of space restrictions, a favorable location, or other reasons, it may be possible to make the structure liquefaction-resistant by designing the foundation elements to resist the effects of liquefaction.

The third option involves mitigation of the liquefaction hazards by improving the strength, density, and/or drainage characteristics of the soil. This can be done using a variety of soil-improvement techniques, some of which are as discussed below.

The main goal of most soil-improvement techniques used for reducing liquefaction hazards is to avoid large increases in pore-water pressure during earthquake shaking. This can be achieved by densification of the soil and/or improvement of its drainage capacity.

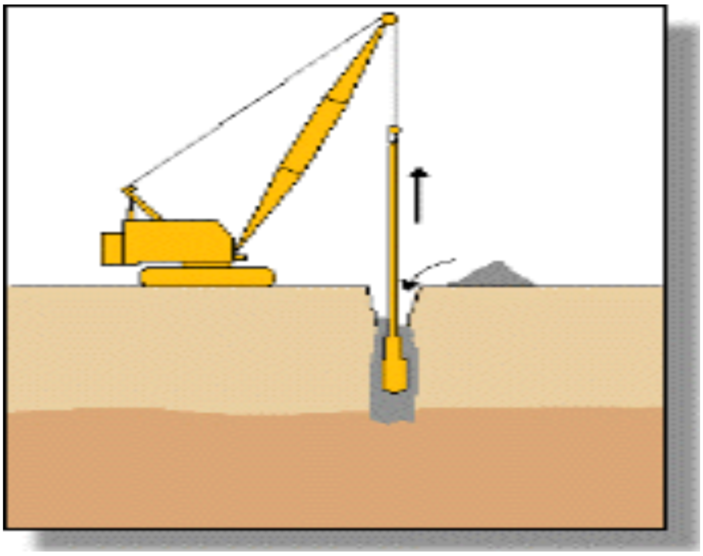


Figure 1. Dynamic Compaction

Vibroflotation: This involves the use of a vibrating probe that can penetrate granular soil to depths of over 30.5m (100 feet). The vibrations of the probe cause the grain structure to collapse thereby densifying the soil surrounding the probe. To treat an area of potentially liquefiable soil, the VIBROLOT is raised and lowered in a grid pattern. Vibro Replacement is a combination of vibroflotation, with a gravel backfill, resulting in stone columns, which not only increases the amount of densification, but provides a degree of reinforcement and a potentially effective means of drainage.

Dynamic Compaction: Densification by dynamic compaction is performed by dropping a heavy weight of steel or concrete in a grid pattern from heights of 4.56m (30 ft.) to 30.5m (100 ft.). It provides an economical way of improving soil for mitigation of liquefaction hazards. Local liquefaction can be initiated beneath the drop point, making it easier for the soil grains to densify. When the excess pore-water pressure from the dynamic loading dissipates, additional densification occurs. As illustrated in Figure 1, above, however, the process is somewhat invasive; the surface of the soil may require shallow compaction, with possible addition of granular fill, following dynamic compaction.

Stone Columns: As described above, stone columns are columns of gravel constructed in the ground. Stone columns can be constructed by the vibro-flotation method. They can also be installed in other ways, for example, with help of a steel casing and a drop hammer, in which the steel casing is driven in to the soil and gravel is filled in from the top and tamped with a drop hammer as the steel casing is successively withdrawn.

Compaction Piles: Installing compaction piles is a very effective way of improving soil. Compaction piles are usually made of pre-stressed concrete or timber. Installation of compaction piles both densifies and reinforces the soil. The piles are generally installed in a grid pattern and are generally driven to depth of up to 18.3m (60 ft.).

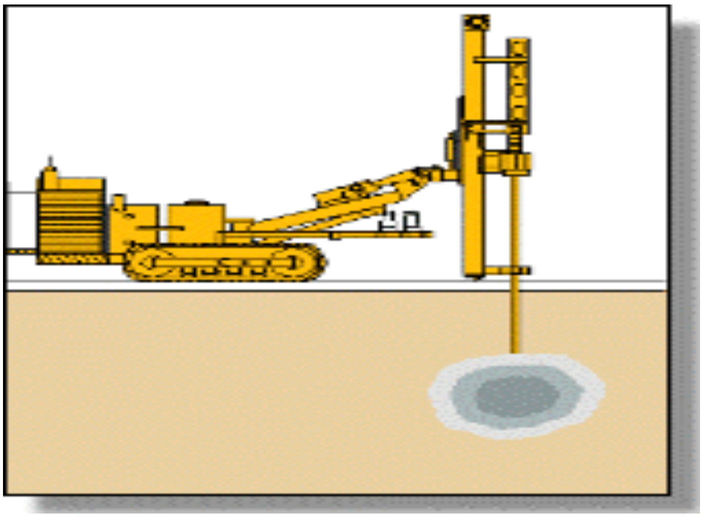


Figure 2. Compaction Grouting

Compaction Grouting: Compaction grouting, as shown in Figure 2, is a technique whereby a slow-flowing water/sand/cement mix is injected, under pressure, into a granular soil. The grout forms a bulb that displaces, and hence densifies, the surrounding soil. Compaction grouting is a good option if the foundation of an existing building requires improvement, since it is possible to inject the grout from the side or at an inclined angle, to reach beneath the building.

Soil-Mixing/Deep-Mixing Wet: Presented here is an example of actual soil-stabilization used to improve the in-situ soil for an ISFSI pad foundation at an existing nuclear power plant in the US.

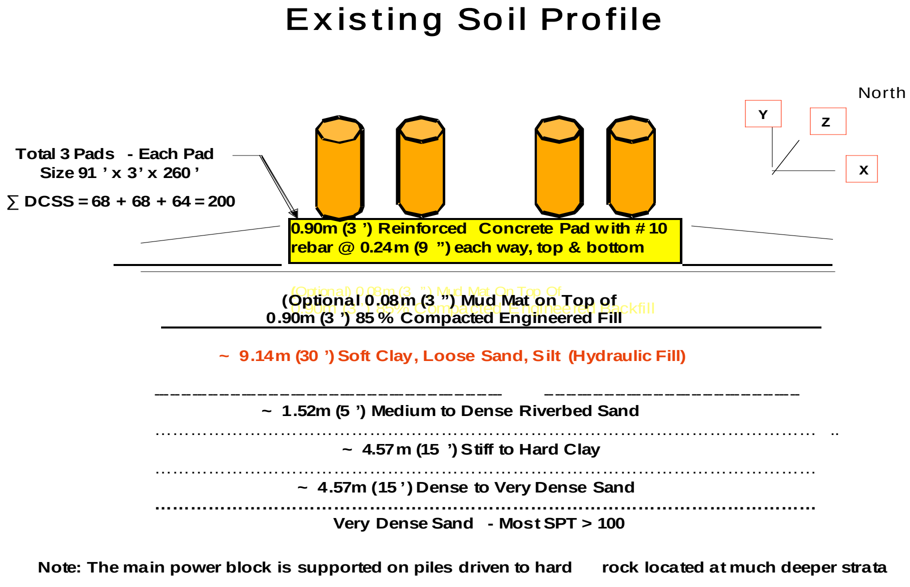
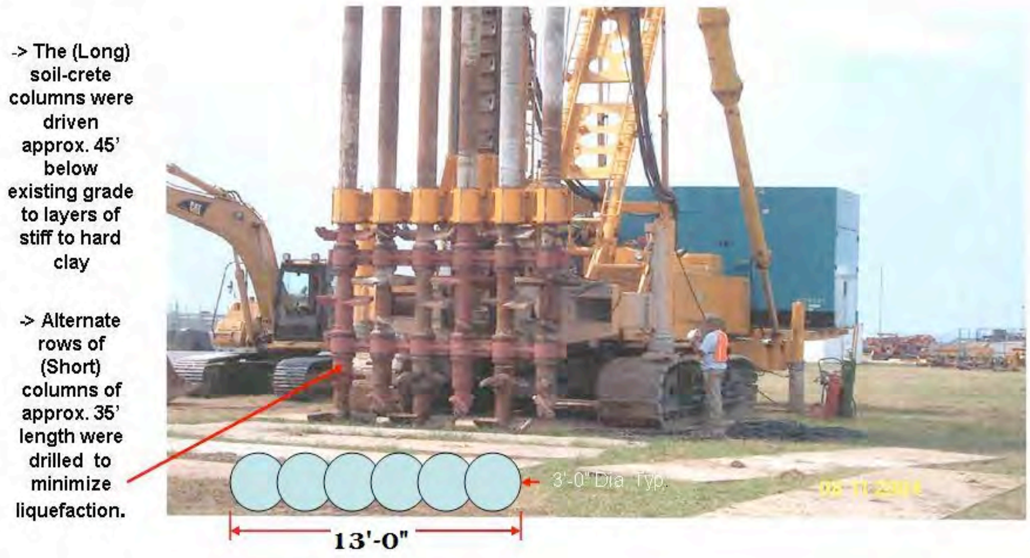


Figure 3. In-situ Soil Profile and ISFSI Pad Arrangement

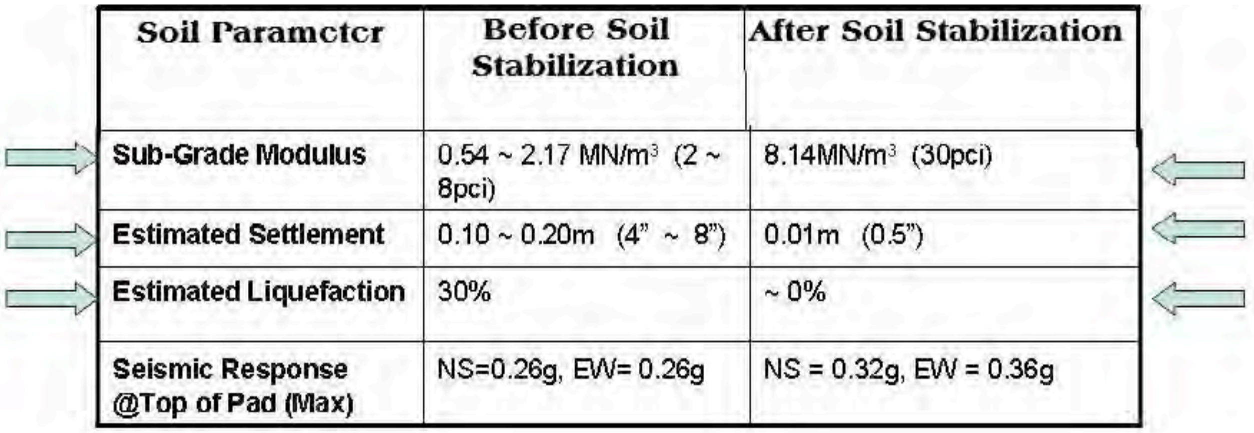


-> The (Long) soil-crete columns were driven approx. 45' below existing grade to layers of stiff to hard clay

-> Alternate rows of (Short) columns of approx. 35' length were drilled to minimize liquefaction.

Approx. ~ 4 meter

Figure 4. Soil-crete Columns Drill Rig



Soil Parameter	Before Soil Stabilization	After Soil Stabilization
Sub-Grade Modulus	0.54 ~ 2.17 MN/m³ (2 ~ 8pci)	8.14MN/m³ (30pci)
Estimated Settlement	0.10 ~ 0.20m (4" ~ 8")	0.01m (0.5")
Estimated Liquefaction	30%	~ 0%
Seismic Response @Top of Pad (Max)	NS=0.26g, EW= 0.26g	NS = 0.32g, EW = 0.36g

Table 1. In-situ Soil Properties Before and After Soil-stabilization

Benefits of Soil Stabilization: As seen in the table above, there is a clear evidence of improved and strengthened soil as a result of soil stabilization. The potential of settlement was reduced from estimated 10.2 cm (4") to 20.4cm (8") to approximately 1.28 cm (½") only. The potential for liquefaction was reduced from estimated 30% for existing soil, to almost none, by drilling in-place (short) columns in between the (long) load-bearing soil-crete columns. Sub-grade modulus of soil underneath the reinforced concrete pad was strengthened from 1.36MN/m^3 (5pci) to 8.14MN/m^3 (30pci), required per the licensing document Certificate of Compliance. Note that the seismic response of the concrete pad was increased by 27%, in an EW direction and 38%, in an NS direction, resulting in more robust pad design. Other benefits of soil stabilization were as follows:

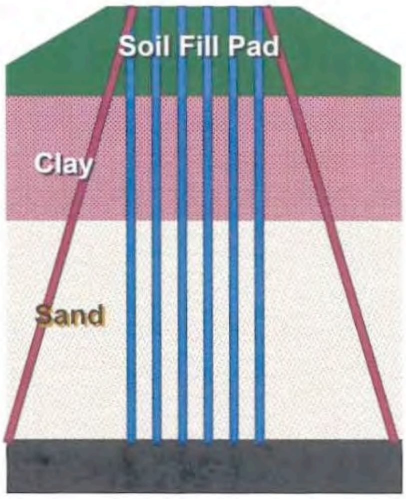
- engineered Fill Depth was reduced from 4.27m (14') to 0.91m (3')
- Reduced Length of East Pad 75m (246') from 79.3m (260')

Verification of Improvement: A number of methods can be used to verify the effectiveness of soil improvement. In-situ techniques are popular because of the limitations of many laboratory techniques. Usually, in-situ tests are performed to evaluate the liquefaction potential of a soil deposit before the improvement was attempted. With the knowledge of the existing ground characteristics, one can then specify a necessary level of improvement in terms of in-situ test parameters. Performing in-situ tests after improvement has been completed allows one to decide if the degree of improvement was satisfactory. In some cases, the extent of the improvement is not reflected in in-situ test results until some time after the improvement has been completed. Subsequent to the improvement, typically NRC inspectors will verify the claims of soil improvement, prior to allowing of pouring of the concrete for ISFSI pads. The NRC Inspection Procedure IP- 60856, “Review of 10 CFR 72.212(b) Evaluations”, Appendix A, provides guidance for a review of ISFSI Storage Pad Design, as a part of a review of 10 CFR 72.212(b) evaluations.

Analyses and Design Details: The out-of-plane flexibility of the concrete ISFSI pad, when evaluating the seismic response of the DCSS, should be accounted for. Typically the ISFSI pad (also referred as base-mat) is a very rigid element in out-of-plane, because of the support afforded by closely spaced piles. Nevertheless, the out-of-plane flexibility of the base-mat needs to be considered in the soil structure interaction (SSI) analysis. Investigating the influence of three parameters, pad flexibility, soil properties, and cask arrangement, on the seismic response of the cask are among some of the most critical steps of any analyses to demonstrate the adequacy of ISFSI foundation to comply with 10 CFR Part 72.212 requirements.

If the fundamental frequency of the cask in the lateral direction lies within the resonant band of the response spectrum, higher amplification could occur at the centre of gravity (CG) of the cask. The seismic stability of the DCSS is based on the seismic acceleration at the CG of the cask and not based on the peak ground acceleration (PGA) at the top of the pad. The analyses of the ISFSI must consider the seismic response at the CG of the DCSS as a basis for acceptance. Although not a safety-related structure, the ISFSI foundation analysis must include an SSI and must address liquefaction potential (10 CFR 72.212(b)(2)). Some times the soil remediation efforts are unable to achieve acceptable accelerations. Preliminary investigations may conclude that using piles may have the highest potential for success. If piles are used, the effects of torsion should be considered. SSI does not capture 3-D effects (such as torsion). An asymmetrically loaded pad will have a torsional dynamic response. SSI does not capture non-linear boundary conditions (i.e., does not account for the fact that piles cannot take tension). To investigate the torsional response of the structure (because of N-S or E-W response of an eccentrically loaded structure), an analytical model that simulates the effect of piles within soil has to be generated.

Top of the ISFSI Pad



Vertical (blue) and Battered (red) Piles supported on Bedrock

Figure 5. Piles supported ISFSI pad

The SSI analysis needs to compute the peak horizontal acceleration at the top of the base-mat for non-liquefied soil conditions with and without a loaded DCSS, in the transverse direction and in the longitudinal direction. These acceleration time histories should then be used in a subsequent analysis to calculate the resulting accelerations at the centre of gravity of the DCSS. The analysis must show that the amplification of the seismic accelerations caused by the resonance of the DCSS with the ground motions is minimal, and that the response at the centre of gravity of the DCSS is within the preapproved limits. Thus for both conditions, with and without the DCSS, the accelerations in both longitudinal and transverse directions has to be below accelerations that were used for qualifying the DCSS by the vendor. The pile foundation must meet the requirements of the CoC, and the structural performance of the foundation must meet the applicable acceptance criteria during a safe-shutdown earthquake or the applicable seismic criteria for the specific site.

4 CONCLUSION:

In-situ soil stabilization has significant effects on the dynamic response of the structure. Future liquefaction potential can be reduced or even eliminated by engineering and stabilizing the sub-grade. This paper has addressed a very broad overview of some of the approaches that could be, and have been used by ISFSI licensees, to enhance the in-situ soil capacities, and to provide sub-strata for founding the reinforced concrete supporting pad for storage of DCSS, when subjected to a design basis seismic event. The potential for any liquefaction of loose soils triggered by a seismic event can be either minimized, or even eliminated altogether by selecting an appropriate arrangement of piles. The safety objectives of 10 CFR Part 72 can be achieved by carefully selecting an adequate soil remediation technique, ideal for a given site, and still meet the seismic demands for the ISFSI installation.

5 REFERENCES

Baker, Hayward. Hayward Baker Inc., A Keller Company (2003), USA, www.haywardbaker.com