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ABSTRACT

This paper describes procedures used to design and qualify unanchored equipment to survive seismic events to the PC = 4 level in a moderate seismic area. The need for flexibility to move experimental equipment together with the requirements for remote handling in a highly-radioactive non-reactor nuclear facility precluded normal equipment anchorage. Instead, equipment was designed to remain stable under anticipated DBE floor motions with sufficient margin to achieve the performance goal. The equipment was also designed to accommodate anticipated sliding motions with sufficient margin. The simplified design criteria used to achieve these goals were based on extensive time-history simulations of sliding, rocking, and overturning of generic equipment models. The entire process was subject to independent peer review and accepted in a Safety Evaluation Report. The process provides a model suitable for adaptation to similar applications and for assessment of the potential for seismic damage of existing, unanchored equipment.

In particular, the paper describes:

- Two dimensional sliding studies of deformable equipment subject to 3-D floor excitation as the basis for simplified sliding radius and sliding velocity design criteria.

- Two dimensional rocking and overturning simulations of rigid equipment used to establish design criteria for minimum base dimensions and equipment rigidity to prevent overturning.

- Assumed mode rocking analyses of deformable equipment models used to establish uplift magnitudes and subsequent impacts during stable rocking motions. The model used for these dynamic impact studies is reported elsewhere[1].

INTRODUCTION

Seismic qualification of equipment within the FCF argon cell presented a unique technical challenge. The conventional solution to seismic loading of equipment is to anchor the equipment. It was recognized early in the project that experience with the remote operation of newly-developed equipment in the limited space available would likely lead to requirements to shift the equipment locations. Anchorage of new equipment after the cell was sealed would also be very difficult. Moreover, loads transmitted by the equipment during a seismic event to the cell liner would present an additional challenge to the liner. The cell liner is the primary confinement of radioactive material, and breach of this confinement during an earthquake is the most severe accident scenario. For these reasons the project chose to bypass conventional anchorage of equipment in the argon cell in favor of engineered seismic qualification of equipment in an unanchored state.

The seismic concerns for equipment consist of:

1) overturning, rocking or sliding of equipment resulting in damage to the equipment, its connecting cables, or adjacent equipment and structures.

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2) stresses and displacements in the equipment resulting in loss of function either during or following the seismic event.

The latter issues must be addressed by both anchored and unanchored equipment. These issues are not normally very severe for equipment because equipment is usually designed to displacement criteria and the stresses are quite small. For unanchored equipment these issues are somewhat less of a concern because sliding acts as a seismic isolation feature reducing the accelerations seen by the equipment. However, impact stresses associated with stable rocking or sliding can be of concern for unanchored equipment.

Anchored equipment addresses the first issues directly by preventing overturning, rocking and sliding. Unanchored equipment must either assure by design and analysis that the phenomena do not occur or address the effect of these phenomena.

The project approach to the concerns of overturning, rocking and sliding are:

1) assure that equipment will not overturn with sufficient controlled margin to achieve the project performance goal of 10^{-5} annual probability of exceedence;

2) assure that equipment either will not rock or, if rocking is expected under DBE conditions, the expected rocking is considered in the design of the equipment using normal structural design margins to achieve the performance goal;

3) quantify the maximum expected displacement and velocity due to sliding and include this design motion in the equipment design criteria.

OVERTURNING

Overturning is a catastrophic response to the horizontal and vertical accelerations induced by the seismic floor motions. It can be prevented by providing a sufficiently broad base compared to the height of the equipment center of gravity. This section describes the analyses used to quantify the minimum ratio of the equipment base dimension to the height of the center of gravity needed to assure that overturning would not occur.

The initial studies considered a rigid body model of the equipment and used static analysis, linear response spectrum analysis and non-linear time-history analysis in conjunction with the argon-cell-floor seismic response spectra and time histories. The rocking motion of a rigid body on a flat surface is a strongly non-linear problem because of the impacts which occur when the flat base of the equipment returns to strike the floor. The linearized model used in the response spectrum analysis avoided this singularity by substituting a linear restoring force. The stiffness of the restoring force was chosen so that the elastic work done by the linear restoring force equaled theincrease in the gravitational energy required to tip the center of gravity of the rigid body to a point directly over the tipping axis. This gross simplification only has validity for motions which are close to overturning.

The results of this linear response spectrum analysis can be interpreted as a predicted stability limit for overturning. The limit depends on two geometric properties of the rigid body, the height of the center of mass of the rigid body above its base, h, and the ratio of the base radius to h. This latter stability parameter is termed α; larger values of α make the equipment more stable. The analysis also shows that, for fixed α, increasing the size of the equipment, ie., increasing h, increases equipment stability.

The exact nonlinear equations can be integrated numerically to simulate response to floor accelerations. This requires an impact assumption when the flat base of the rigid body strikes the flat floor during rocking. Using a conservative assumption that no energy is lost in the impact, 600 cases were evaluated in a parametric study. The results of this study confirmed the adequacy of the linear model in predicting the stability limit. Figure 1 shows some of these cases plotted in the h - α parameter plane with open circles showing stable solutions and solid circles showing unstable simulations. The stability limit predicted by the linearized rocking model is shown as a continuous line.

Another approach to the overturning stability limit is to assume that the equipment is deformable and that it builds up energy in its deformation modes in response to the floor motion. Having reached its peak response energy, this energy is assumed to be available to overcome the stabilizing gravity potential represented by the body geometry. Such a linear response spectrum analysis indicates that if the fundamental frequency of deformation is above 3 Hz., the total deformation energy is not more than the energy in the linear tipping model. Thus the stability criteria associated with this analysis is nearly identical to that shown for the linear response spectrum tipping model.

The basic approach used to address seismic hazards requires a controled margin to ensure that the equipment will not overturn in a more-severe less-probable seismic event than the design basis earthquake. This is normally achieved in design using a factor of safety of about 4 in conjunction with an abnormal event multiplier of 1.7. The result is a factor of 4/1.7 = 2.35. In the overturning analysis this factor was applied to the stability criteria predicted by the various analyses by increasing the parameter α by 2.35. Figure 1 show the stability limit given by the deformable body analysis increased by this factor.

Finally, the figure shows the FCF design criteria for overturning of unanchored equipment in the air and argon cells. The equipment must have a center of gravity greater than 6 inches and a stability parameter, α, greater than 0.52 for h > 20 inches. In the region 6 < h < 20 in., the minimum α decreases linearly with h. In addition, the equipment is required to have a natural frequency above 3 Hz.

ROCKING

The overturning criteria has sufficient margin to assure that rigid equipment will not overturn with an exceedence probability of less than 10^{-5} per year. However, deformable equipment could develop sufficient energy to cause tipping (but not overturning). This stable rocking motion has the potential for damaging the equipment base and must be considered in the equipment design. A first attempt to address this issue, based on energy considerations, resulted in criteria which were too restrictive for design. In order to remove the excessive conservatism in the energy based criteria, a special purpose computer code was written to analyze stable rocking motions of deformable equipment. The code integrates the coupled equations of rigid body rocking and equipment deformation using the argon cell floor accelerations and the equipment-specific deformation parameters as input. It calculates if rocking will occur, and if so, the number and magnitude of the impacts. Extensive applications of this code indicate that equipment rocking is not a problem for FCF equipment.

SLIDING

The potential for sliding can be inferred from the response spectra. In the limit of no frictional resistance to sliding, the equipment stays fixed in space while the floor moves. The maximum relative displacement between the floor and the equipment is given by the low frequency portion of the displacement spectra which is 5.5 inches. For sufficiently large friction, the equipment does not slide and the relative motion is zero. For intermediate values of friction, rigid equipment will slide with maximum displacement and

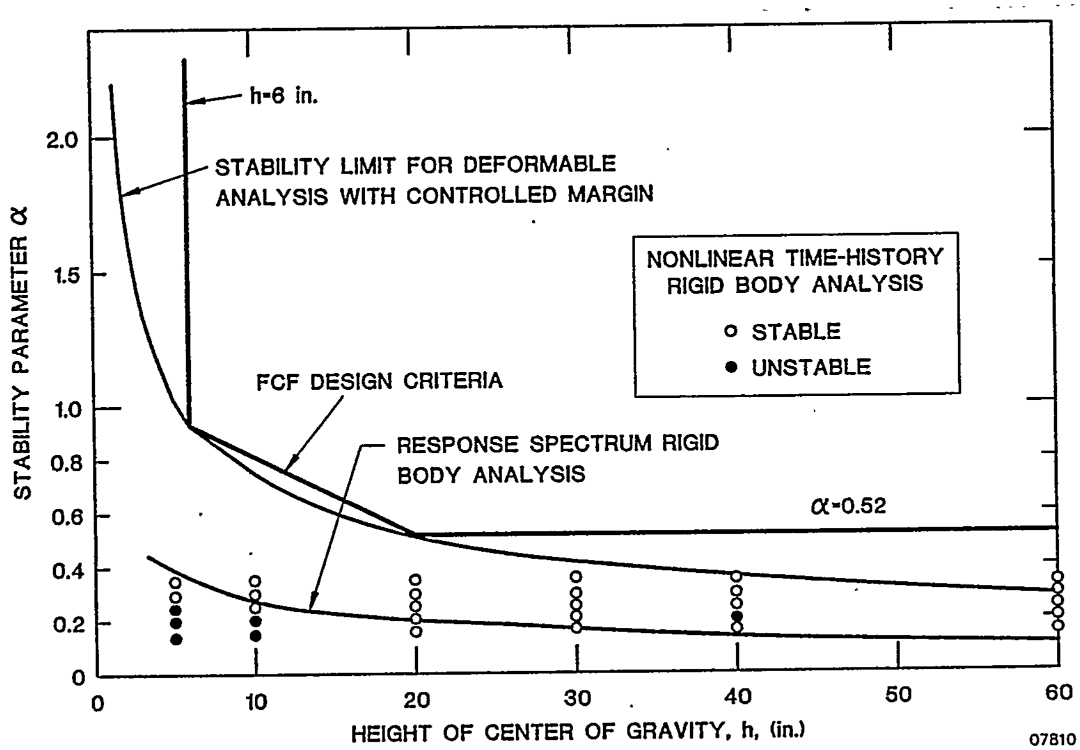

Figure 1. Stability criteria from overturning analyses and design criteria for unanchored equipment in the air and argon.

velocity between these values. If the equipment is not rigid, there is potentially an interaction between the equipment deformation and the sliding. If the deformation modes are symmetric and/or the equipment frequency is sufficiently high compared to the frequency content of the floor motion, this interaction will have only a small effect on the relative position and velocity of the equipment. However, if the equipment frequency is sufficiently low and the deformation mode is not symmetric about a vertical axis, a "walking" effect can occur and the relative displacement can be substantially greater than that of rigid equipment. This walking effect occurs because during one half of a vibration cycle the floor normal reaction is increased; this increases the frictional resistance and limits horizontal motion in one direction. During the second half cycle the normal force is reduced; this reduces the frictional resistance and allows more horizontal motion in the opposite direction.

To quantify this potential walking phenomena, a mathematical model of a deformable sliding body was developed and parametric studies were conducted using the floor seismic time histories. The effects of friction coefficient, deformable mass participation, deformation frequency, and angle of asymmetry of the deformation were studied. 575 cases were calculated with the following conclusions:

1) The qualitative conclusions for rigid and symmetrically deformable bodies described above were confirmed;

2) walking can occur and is most severe for unsymmetric, low-frequency, deformation modes with large participating mass and low, but non-zero, friction;

3) if the deformation frequency is above 3 Hz., the maximum relative displacement is 6 in. and the maximum relative velocity is 13 in/sec. regardless of the mass participation factor or the coefficient of friction.

As a result of these studies the sliding criteria used in the design of FCF equipment are: frequency greater than 3 Hz., sliding radius of 6 in., and sliding velocity of 13 in/sec. The controlled margin associated with these criteria is contained in the design margins for assessing the loads and deformations associated with impacts.

CONCLUSIONS

In a moderate seismic environment (the facility DBE had a 0.14 g zpa ground spectra) it is feasible to address equipment seismic qualification without anchoring the equipment. Simple design procedures based on the building floor spectra can be developed to assure that equipment does not overturn. Allowance for sliding and sliding impact can be specified. Base impacts due to stable rocking can be calculated for specific equipment and the potential for base deformation assessed. This is an analysis-intensive alternative to traditional anchorage and can only be justified under unusual circumstances.

REFERENCES

[1] Moran, T. J., "Uplift and Rocking of a Deformable Body Subject to Base Excitation", Proceedings of the Symposium on Natural Hazard Phenomena and Mitigation at the 1995 ASME/JSME Joint Pressure Vessel and Piping Conference, Honolulu Hawaii.