Assessment of Structures and Equipment Reported as Dominant Contributors to Seismic Risk

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Abstract

This paper identifies and discusses the primary contributors to seismic risk of nuclear plants with SSE acceleration levels between 0.12g and 0.25g in low-to-moderate seismic regions as obtained from reviews of existing seismic PRAs. Approximate fragility estimates are presented and the sources for those estimates are outlined. It is concluded that for ground motions less than about 0.3g the predominant sources of seismic risk are loss of offsite power coupled with random failure of the emergency diesels, non-recoverable circuit breaker trip due to relay chatter, unanchored equipment, unreinforced non-load bearing block walls, vertical water storage tanks, systems interactions and possibly soil liquefaction.

1. Introduction

The objective of a seismic probabilistic risk assessment (PRA) is to estimate the frequencies of occurrence of earthquake-induced accidents that may lead to different levels of damage (e.g., early deaths, latent cancer fatalities, and property damage). The basic elements of a seismic PRA are: seismic hazard analysis of the site, fragility evaluation of the plant structures and equipment, analysis of the plant systems and accident sequences, and assessment of the consequences [1, 2]. In the last four years, seismic PRAs on seven U.S. nuclear power plants - Zion, Indian Point 2 and 3, Limerick, Seabrook, Midland, Millstone 3 and Oconee - have been published. Many other unpublished seismic PRAs have been performed or are being performed. All of the published U.S. seismic PRAs and nearly all of the unpublished ones have been conducted on plants in the eastern portion of the U.S. in regions of low-to-moderate seismic activity with safe shutdown earthquakes (SSE) between 0.12g and 0.25g. The comments in this paper are thus primarily applicable for such plants.

A major benefit of the seismic PRA is the insight it provides on the relative safety of different structures, equipment, and systems in the plant, and identification of the dominant risk contributors. Some of the PRAs have indicated that seismic events contribute importantly to the overall plant risks; these and others have helped to identify the strengths and weaknesses of plant safety systems with particular emphasis on seismic events. The existing seismic PRAs and their reviews have underscored the fact that the seismic hazard estimates are highly uncertain. There is a wide difference of opinion between hazard analysts as to the appropriate hazard modeling parameter values for any specific site. This source of uncertainty alone has generally contributed to at least 3 orders of magnitude of uncertainty in the seismic risk estimates. Because of such uncertainty, bottom-line seismic risk numbers have been considered to be suspect and have been primarily used qualitatively. Therefore, for the present, published seismic PRAs should be analyzed from a viewpoint that is not fogged by the seismic hazard issues.

The objective of this paper is to identify those structures, components, and systems which have been commonly reported in seismic PRA studies to dominate the seismic risk at a nuclear plant and to describe some of the fragility data which results in some of these components dominating the seismic risk. The purpose is to identify those components which should be more carefully studied in seismic margin reviews. In this way, the results of seismic PRAs can be used without consideration of the seismic hazard issue.

2. Fragility Data Base

While considering the dominant contributors to seismic risk, one should keep in mind the available sources from which fragility data for these components is derived. For civil structures and passive equipment, fragilities may be derived analytically from existing design information supplemented by other information sources which include:

Knowledge of conservatisms in existing design codes.
Knowledge of conservatisms inherent in seismic response calculations.
Existing research results on inelastic energy absorption.
Existing University and National Laboratory sponsored research on uncertainties in response and strength.
Actual earthquake experience.

Very little fragility data exist for active equipment and fragility descriptions for functional failures cannot always be derived by analysis. The analyst must use a variety of information sources, similarities and limited analyses to develop active equipment fragilities. The information sources available include:

Qualification test data for nuclear components.
Limited fragility data on electrical devices.
Severe shock test data from military programs.
Expert opinion surveys.
Performance in past earthquakes.

Application of these information sources requires judgment of highly experienced engineers. Because the fragility descriptions for active equipment are more subjective than for structures and passive equipment, uncertainties are usually larger.

3. Dominant Contributors to Seismic Risk

From past seismic PRAs, the dominant contributors to seismic risk are consistently [3]:

1) Loss of power
2) Electrical equipment
3) Water storage tanks
4) Civil structures
5) Soil failure (liquefaction)
6) Non-load bearing walls
7) Major NSSS component supports
8) Reactor scram devices
9) Systems-interactions

In most of the more recent and more detailed seismic PRAs, loss of power (station blackout) has been either the overwhelming dominant contributor to seismic-induced core damage or at least a major contributor. A seismic-induced anticipated transient without scram (ATWS) resulting from failure to insert the control rods plus either the loss of the diesel generators or loss of adequate cooling water has also generally been an important contributor to core damage. Some form of large LOCA with containment bypass has often dominated the seismic risk of early fatalities. The most dominant cause of this seismic-induced LOCA has been the seismic failure of major NSSS component (reactor vessel, steam generator, pressurizer, etc.)

supports. Such failures can be postulated to lead to sufficiently high overpressure to cause breach of containment. It should be noted that, with one possible exception, seismic-induced structural failure of the containment has never appeared to be a dominant contributor to seismic risk. The seismic margin of the containment is sufficiently large relative to the margin of other components (primarily NSSS component supports) to prevent a seismic-induced containment failure from having any dominance. Similarly, inertial (dynamic shaking) induced piping failures have also never been reported to be a significant contributor to seismic risk. On the other hand, in some cases where piping interconnects between two buildings and has inadequate flexibility between supports in different buildings, excessive building deflections has been considered to lead to piping failures which result in seismic risk. This observation from seismic PRAs that inadequate piping flexibility and excessive relative support deflections are the more likely contributor to seismic-induced piping failures rather than dynamic shaking effects is totally consistent with observed behavior of industrial facility and fossil fuel power plant piping during past earthquakes with ground motion up to 0.5g.

In summary, seismic margin studies or seismic risk studies at least in low-to-moderate seismic regions should concentrate on the previously listed 9 component categories plus support displacement-induced piping failures. The remainder of this paper will discuss these 9 categories.

4. Loss of Power

Station blackout requires the loss of both the offsite and onsite power. Both sources of power have vulnerable features. For offsite power, the station switchyard with its large yard-mounted switchgear, and ceramic insulators plus the aboveground transmission lines have proven to be vulnerable in past earthquakes. A study of fossil fuel plants in California indicates that the seismic fragility of the plant connection to the power grid is highly variable even when one only considers ground motion records with broad frequency content, and reasonably long duration from about magnitude 6.0 and greater earthquakes. With such ground motion, at least one power plant lost connection to the power grid due to switchyard and transmission line damage at a ground motion of about 0.13g. On the other hand, in a number of cases, plants have stayed on-line with ground motions in excess of 0.5g [4]. A study of this limited data seems to indicate a median fragility (50% frequency of failure) of about 0.30g to 0.35g with high confidence (95%) of a low-frequency (5%) of failure at 0.10g and certainly less than 80% frequency of failure at 0.50g. Analytical studies tend to support these fragility estimates drawn from past earthquake experience. In other words, loss of offsite power is certainly possible in a moderate (0.2g to 0.3g) ground motion but should not be taken as 100% probable as was done in some of the earlier seismic PRA studies.

Once offsite power is lost, the emergency diesel generator must start and operate. In the more recent seismic PRAs where random failures and seismic failures have been coupled, it has been consistently calculated that for ground motion less than about 0.3g the dominant seismic-induced cause of core damage is seismic-induced loss of offsite power coupled with random failure of the diesels. In other words, if one wished to reduce the seismic risk from ground motion less than 0.3g, one should concentrate on increasing the reliability of the diesels rather than performing seismic margin studies or upgrades on other components.

At ground motions in excess of about 0.3g, seismic-induced failures of the diesels become significant contributors to the risk. The diesel generators themselves have not been the low seismic capacity components. In fact, the authors are not aware of a single case where a diesel generator has ever been damaged in any earthquake of any size. The postulated failures have all been with the peripherals such as the fuel oil storage tank, the day tank, the oil cooler tank, the heating and venting ducting, and the lateral support to prevent sliding. The postulated critical failure modes for these peripherals have all been structural modes (i.e., attachment bolt and support failures). Fragilities have primarily been estimated using analytical approaches [1, 2] and have varied from plant-to-plant. However, even for the lowest capacity components, the median capacities have generally exceeded 0.9g and the high confidence, low frequency of failure estimate has generally exceeded 0.3g. These estimates are consistent with the past earthquake experience data base in which emergency diesels and their peripherals have both demonstrated substantial seismic ruggedness. Even so, if one must reduce the seismic risk of nuclear plants for ground motions in excess of 0.3g, seismic PRA results indicate that the peripherals of the emergency diesel generators are strong candidates for further review.

During the Systematic Evaluation Program (SEP) in the United States (1977-1980), batteries and their racks were identified as major seismic-induced risk contributors because of the lack of seismic bracing in the racks and lack of lateral and longitudinal support of the batteries. Fragility testing of batteries has demonstrated that standard 125V DC batteries have substantial seismic ruggedness (high confidence, low frequency of failure ground motion estimate of about 0.7g) when properly supported. The problems with battery racks identified in the SEP appear to have now been corrected at all U.S. nuclear power plants. Batteries and their racks have never been identified in a seismic PRA to be a significant contributor to risk. Unless a seismic walkdown of a nuclear plant identifies an obviously deficient battery rack or longitudinal support of batteries in such racks, batteries and their supports do not appear to be a seismic margin or seismic risk issue in low-to-moderate seismic regions.

5. Electrical Equipment

In the majority of seismic PRAs, it has been assumed that operators would recover from seismic-induced relay chatter and circuit breaker trip. Whenever this assumption has been made, electrical equipment such as, motor control centers and in-plant low-voltage and metal-clad switchgear, have never been reported to be significant contributors to risk. This finding is consistent with experience in past earthquakes and the conclusions of the Senior Seismic Review and Advisory Panel (SSRAP) [4, 5] which reported that such equipment had an inherent seismic ruggedness so long as it was properly anchored. There does not appear to be a single case of a reported seismic-induced structural failure of this equipment or its cabinet or failure to operate after the earthquake has ended within the U.S. earthquake experience data base so long as this equipment remains anchored. Furthermore, proper anchorage is easy to achieve. Seldom has anchorage of this equipment failed in industrial and fossil fuel plants subjected to ground motions up to about 0.5g. Within the experience of the authors, anchorage of such equipment at nuclear plants in the U.S. is generally better and at-least-as-good as that in the data base plants subjected to past occurrences of strong ground motion. Clearly, unless a seismic walkdown indicates poor anchorage practice at a nuclear plant, structural failures of such equipment does not appear to be an important seismic margin or seismic risk concern in low-to-moderate seismic regions.

However, relay chatter and circuit breaker trip are another matter. Seismic PRA sensitivity studies which assume that there is relatively significant probability that the operators cannot recover from relay chatter-induced circuit breaker trip have shown that this electrical equipment is a major contributor to seismic risk of core damage. Qualification and fragility test data as well as earthquake experience has demonstrated that some relays do chatter at low input shaking levels. Thus, one cannot dismiss the possibility of relay chatter at ground motion levels much above the SSE for which the equipment was qualified.

Much further work is needed to properly treat the issue of relay chatter in seismic PRAs. Detailed circuit design, detailed information on the types of relays present, the probability that relay chatter leads to breaker trip, and the probability that the operator cannot recover from breaker trip must all be considered.

6. Water Storage Tanks

Past earthquake experience has demonstrated that steel flat-bottom, skirt-mounted, and leg-mounted vertical water storage tanks have highly variable seismic capacity. Some tanks have failed at ground motions less than 0.2g while many tanks have survived 0.5g motions. Seismic design practices have been highly varied even in the nuclear power industry. Prior to about 1975, most tank designs were based upon the improper assumption that for impulsive effects the tank could be treated as rigid and be designed for the support acceleration rather than an amplified spectral acceleration. In most cases, about a factor of 2 unconservatism was introduced by this approach. Such unconservatism removes most of the conservatism introduced by other parts of the design process. As a result, tank failures at ground motions only slightly greater than the SSE level must be considered possible. Seismic fragilities can be estimated for tanks by analytical methods [1, 2]. Published seismic PRAs have shown high confidence, low probability estimates as low as 0.2g with median (50% frequency of failure) estimates as low as 0.5g. Despite such low estimated capacities for some water storage tanks, these tanks have never been reported in a seismic PRA to be a significant contributor to risk. There is reduncancy of water storage at a plant and tank design has been highly non-standard even at a single nuclear plant. Thus, while one tank may have low seimic capacity, some other tank has high seismic capacity. Here is a case where non-standardization has proven to be very beneficial. If all tanks had been designed the same, the benefits of redundancy in a seismic event would have been lost.

7. Civil Structures

Category I civil structures which have been designed for seismic events have substantial seismic capacity unless a design or construction deficiency occurs. Earthquake experience has shown that one would seldom expect severe structural distress for structures designed similar to nuclear plant structures at ground motions less than 0.5g. Seismic PRA studies on low-to-moderate SSE design plants have reported high confidence, low probability of failure capacities for most civil structures of about 0.5g with median capacities around 1.5g. Even so, at least one weak-link civil structure with high confidence, low probability capacity around 0.3g and median capacity around 0.9g is found in most published PRAs. Weak-links have been generally due to low ductility in the shear wall or braced frame design, weak floor diaphragms due to large cutouts, foundation failure, or building sliding.

Despite the rather high capacity of even the weak-link civil structures, such structures have generally been reported to be significant contributors to the seismic risk. This situation arises because of the conservative assumption made in seismic PRAs that severe structural distress to the civil structure results in failure of all components within the structure. This conservative assumption must be reevaluated before one can actually assess whether or not civil structures are significant contributors to risk.

Building-to-building impact due to an inadequate seismic gap between buildings has also been identified as a major contributor to seismic risk in some PRAs. However, these PRAs may have overemphasized the damage that might result from such impacts. Experience shows that building impacts tend to only lead to local damage.

8. Soil Liquefaction

To date, no published seismic PRA has identified soil liquefaction as a dominant contributor to risk because their site conditions have not been particularly vulnerable to liquefaction. However, several nuclear plants in the U.S. are founded on soils for which one would expect significant probability of severe soil liquefaction effects at effective ground accelerations of 0.3g to 0.5g from magnitude 6 and greater earthquakes. Such liquefaction is likely to result in tilting of surface founded buildings (diesel generator building is one example) and severing of interconnected buried piping between buildings. For these sites, liquefaction would be expected to be the dominant contributor to seismic risk from effective ground accelerations greater than about 0.3g.

9. Non-Load Bearing Walls

Eastern U.S. nuclear plants have often used either unreinforced or lightly reinforced non-load bearing masonry walls as room dividers and fire barriers. Such walls have demonstrated very poor performance in past earthquakes. Both earthquake experience and seismic analyses indicate that one can expect median capacities of such walls to generally lie in the 0.3g to 0.4g range even after these walls have been strengthened to satisfy the SSE ground motion. Often, these walls have been placed around the battery racks and as fire barriers separating the individual diesel generators where their failure might damage either the batteries or diesels. These walls have seismic capacities similar to that of offsite power. Thus, these walls have sometimes been significant contributors to core damage from station blackout. Here is an example where walls built to reduce fire risk without adequate consideration of seismic risk have increased the seismic risk and possibly the overall risk (fire plus seismic). Clearly, such walls are a primary candidate for seismic margin reviews for earthquakes significantly greater than the SSE level.

10. Major NSSS Component Supports

Published seismic PRAs have indicated that the major NSSS components (reactor vessel, steam generator, pressurizer, etc.) have very substantial seismic capacity. Typically, the weak-link has been reported to be the component supports where the fragility estimates are based upon analytical evaluations [1, 2]. Such studies have indicated high confidence, low frequency of failure capacities generally exceeding 0.5g to 0.6g with median capacities generally exceeding 1.5g. In other words, very large seismic margin results beyond the SSE levels (0.12g to 0.25g) because of large conservatism in the design practice for such supports. Even with such high capacities, these component supports have consistently appeared to be the dominant contributor to seismic-induced early fatalities because of the severe consequences of such support failures. In each of the published seismic PRAs, seismic-induced risk of early fatalities only begins to become significant at effective ground accelerations in excess of 0.6g. Such severe ground motion is extremely unlikely in low-to-moderate seismic regions and significantly exceeds the ground motion levels for which experience data exists for fossil fuel and heavy industrial plants in California. Thus, the fragility estimate of these component supports must be based purely on analytical studies since no experience data exists at these high ground motion levels.

11. Reactor Scram Devices

In seismic PRAs, the seismic-induced failure to fully insert the control rods has consistently shown up as the dominant contributor to a seismic-induced ATWS which in turn has often been a moderate contributor to the seismic risk of core damage. The predominant seismic causes of failure to fully insert the control rods have been reported to be seismic failure of the control rod drive system and seismic-induced severe distortion of the core geometry. Fragility estimates are generally quite high with high confidence, low frequency of failure ground motion estimates between 0.3g to 0.4g and median fragilities around 1.0g. These estimates must generally be based on NSSS supplied proprietary studies and tests so that independent verification is nearly impossible. No earthquake experience data exists beyond about 0.15g for these components since they do not exist on fossil fuel or heavy industrial plants.

12. Systems Interactions

No systematic or exhaustive study of system interaction (seismic failure of a non-seismic designed non-safety component leading to failure of a safety component) has been performed in any of the published seismic PRAs. However, plant walkthroughs have been conducted as part of each of these PRAs and the most apparent systems interactions have been incorporated. Several such interactions have been found to be significant contributors to seismic risk and are eliminated as a result of the seismic PRA. Some examples are presented. Hung ceilings in control rooms can fall. Such failures have occurred in fossil fuel plants with ground motions in the 0.3g to 0.5g range where operators have been injured and access to control boards have been severely impaired due to hung ceiling debris. No damage resulted to the control board but operator performance was impaired. Cases where non-seismic designed hung lighting, space heaters, and block walls might fall on batteries and exposed tubing and controls of diesel generators have also been observed in seismic PRA walkthroughs. Non-seismic designed fill lines into safety-related water storage tanks have not been valved close to the tank and have been attached to the tank in a way such that their failure would drain the tank. Each of these potential failures could have a profound effect on the seismic risk in the 0.2g to 0.4g ground motion range where seismic PRAs would otherwise show the seismic risk to be very small. For such ground motion, a systematic review of systems interactions would probably result in greater reduction in seismic risk than would a seismic upgrade or reevaluation of safety equipment for earthquakes greater than the design SSE level.

13. Conclusions

This paper identifies and discusses the primary contributors to seismic risk of nuclear plants with SSE levels between 0.12g and 0.25g in low-to-moderate seismic regions as obtained from reviews of existing seismic PRAs. Approximate fragility estimates are presented and the sources for those estimates are outlined.

It is concluded that for ground motions less than about 0.3g the predominant sources of seismic risk are loss of offsite power coupled with random failure of the emergency diesels, non-recoverable circuit breaker trip due to relay chatter, unanchored equipment, unreinforced non-load bearing block walls, vertical water storage tanks, systems interactions and possibly soil liquefaction. For other sources of seismic risk to dominate requires ground motions substantially in excess of 0.3g. A significant risk of seismic-induced early fatalities from the nuclear plant requires ground motion substantially in excess of 0.6g.

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