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CRITERIA FOR DESIGN OF THE YUCCA MOUNTAIN STRUCTURES, SYSTEMS AND COMPONENTS FOR FAULT DISPLACEMENT

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ABSTRACT

The DOE intends to design the Yucca Mountain high-level waste facility structures, systems and components (SSCs) for fault displacements to provide reasonable assurance that they will meet the preclosure safety performance objectives established by 10 CFR Part 60. To the extent achievable, fault displacement design of the facility will follow guidance provided in the NRC Staff Technical Position (1). Fault avoidance will be the primary design criterion, especially for spatially compact or clustered SSCs. When fault avoidance is not reasonably achievable, expected to be the case for most spatially extended SSCs, engineering design procedures and criteria or repair and rehabilitation actions, depending on the SSC's importance to safety, are provided. SSCs that have radiological safety importance will be designed for fault displacements that correspond to the hazard exceedance frequency equal to their established seismic safety performance goals. Fault displacement loads are generally localized and may cause local inelastic response of SSCs. For this reason, the DOE intends to use strain-based design acceptance criteria similar to the strain-based criteria used to design nuclear plant SSCs for impact and impulsive loads.

I. INTRODUCTION

To obtain a construction authorization for the proposed high-level waste repository facility at Yucca Mountain, Title 10 of the Code of Federal Regulations, Part 60 (10 CFR, Part 60) requires a demonstration of reasonable assurance that natural phenomena do not unduly compromise either safety functions of structures, systems, and components (SSCs) of the geologic repository operations area (GROA) or radioactive waste containment and isolation. It additionally requires that the option be maintained to retrieve implaced waste during the preclosure time period of the repository operation. The regulation gives safety performance objectives that must be satisfied, but does not provide technical guidance to implement them. Partial technical guidance has been given in the Nuclear Regulatory Commission (NRC) Staff Technical Position (1), but that document also lacks specific technical procedures and criteria for satisfying the preclosure regulatory safety performance objectives. The Staff Technical Position (STP) recommends avoidance of Type I faults (2) when reasonably achievable, but recognizes that fault avoidance may not be possible for all repository SSCs.

As part of its seismic design activity for a geologic repository at Yucca Mountain,

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the U. S. Department of Energy (DOE) has developed methods, procedures and criteria to provide reasonable assurance that the Yucca Mountain facility SSCs will meet the pertinent preclosure safety performance objectives of 10 CFR Part 60 with respect to seismic hazards (3). To issue a license for the repository, the regulation requires the NRC to find that the facility will not constitute an unreasonable risk to the health and safety of the public. The regulation further states that this decision will be based on the standard of reasonable assurance, recognizing that uncertainties exist in technology and knowledge about the natural environment and taking account of these uncertainties in the decision process. Consequently, specific design procedures and criteria must be provided that take account of both uncertainty in determining seismic hazards and in engineering design methods. To quantitatively account for uncertainty and provide an integrated seismic design approach that uses seismic design and acceptance criteria with which engineers and regulators are familar and which provides for SSC-specific seismic safety design depending on the importance of an SSC for radiological and worker safety, the performance goal-based seismic design methodology has been adopted and adapted for the seismic design of the Yucca Mountain facility (3, 4, 5, 6).

Criteria for the design of SSCs for fault diaplacement are provided in the DOE methodology for seismic design of the Yucca Mountain facility (3). For economic reasons, fault displacement hazard generally has been mitigated by fault avoidance. It is recognized, however, that avoidance of all faults with all SSCs will not be possible for the proposed geologic repository at Yucca Mountain. Consequently, specific procedures and criteria for the design of SSCs for fault displacement are required. Available design approaches fall into three general categories: fault avoidance, geotechnical engineering isolation techniques, and structural engineering design to increase structural ductility or to provide for structural modularization. The specific choice of an approach depends on the SSC, its intended function, its configuration, and the geotechnical characteristics of materials on which it is to be founded. It is expected that all of these approaches will be used in the design of the Yucca Mountain facility.

In this paper we discuss the limited experience with the design and performance of both surface and subsurface SSCs to accommodate fault displacement and describe the criteria that the DOE intends to implement for the design of the Yucca Mountain facility (3). Relevant experience with the performance of underground openings that have been subjected to fault displacements is discussed elsewhere in this volume by Nolting (7).

II. EXPERIENCE IN DESIGN OF SURFACE SSCs TO ACCOMMODATE FAULT DISPLACEMENT

The specific issue of whether a nuclear facility can safely accommodate fault offset was extensively evaluated by the NRC staff and the Atomic Safety and Licensing Board during the 20-year licensing renewal review of the General Electric Company Test Reactor (GETR) (8, 9, 10, 11). The GETR, at Vallecitos, California, is located on the surface trace of a thrust fault called the Verona fault. Investigations conducted by the General Electric Company (GE) and reviewed by the NRC staff concluded that the Verona fault, which is apparently structurally related to the Calaveras fault, could have as much as one meter of surface displacement co-seismically with vibratory ground motion from a magnitude 6.5 earthquake. Thus, the GETR facility was re-analyzed for vibratory ground motion defined by a USNRC Regulatory Guide 1.60 response spectrum anchored at 0.6g and combined with a 1.0-meter fault displacement beneath the reactor building on a plane dipping at 15 degrees to the horizontal.

The stress loads induced by the combined vibratory ground motion and fault displacement were found to be below the conservative cracking threshold capacity of the concrete reactor building. The analysis further showed that, for the geotechnical properties of the GETR facility foundation, fault displacement would be deflected around the heavy, embedded containment structure. Based on these analyses the NRC staff concluded that the GETR SSCs important to safety would perform their intended functions under the combined fault displacement and vibratory ground motion loading. These evaluations and conclusions were reviewed in a public hearing before a panel of the Atomic Safety and Licensing Board and found to be in compliance with the NRC's seismic safety regulations (8).

Other analytic studies of the effects of fault displacement on structures have been reported by Duncan and Lefebvre (12), Berrill (13), and Subramanian, et al. (14). These studies concluded that structures can be designed to withstand fault displacements by providing assurance of the proper level of ductile performance. For heavy, embedded structures the studies performed by Duncan and Lefebvre and Berril indicated that fault displacement would deflect around the structure. Subramanian, et al. (14) performed a simplified analysis of the main waste handling building proposed for the Yucca Mountain facility for combined vibratory ground motion and fault displacement loads. They concluded that for a 0.4g vibratory ground motion design basis, the conditional probability of the waste handling building exceeding a moderate damage state is $2x10^{-3}$ and $5x10^{-2}$ for vertical fault fault displacements of 1 cm and 10 cm respectively.

In addition, simplified analyses performed by Kennedy et al., (15) and ASCE (16) show that well-designed shallow buried piping placed in loose to moderately dense cohesionless soil can withstand fault displacements as large as 6 meters. These results show that well-designed SSCs can conservatively withstand small fault displacements without loss of function.

Experience of a structure's response to vibratory ground motion and a co-seismic fault displacement has been studied by Niccum (17), Selna and Cho (18) and Wyllie (19), who reported investigations of fault displacement through the Banco Central de Nicaragua building during the December 23, 1972 Managua, Nicaragua earthquake. These investigations reported that a fault displacement of 10 - 17 cm deflected around the bank's heavy substructure. This observation is consistent with the analytical results reported by Duncan and Lefebvre (12), Berrill (13), and the GETR analysis (8).

III. EXPERIENCE IN DESIGN OF UNDERGROUND SSCs TO ACCOMMODATE FAULT DISPLACEMENT

Rather than provide a tunnel support structure that has the strength to resist fault movement, the approach in a number of cases has been to first evaluate the necessity for accommodating fault displacement and second, if determined to be necessary, provide a flexible structure that allows deformation without undue disruption of the drift function. An enlarged tunnel cross-section may also be indicated as part of the design solution. In addition to flexibility, the support structure must maintain stability, since rock quality in the vicinity of a fault often is low enough to require stabilization. Either rockbolts and mesh or lining systems can be used.

A. Rockbolts and Mesh

Rockbolts, wire mesh, and straps form an inherently flexible ground support system that provides reasonable assurance of achieving the established safety performance and is relatively easy to maintain and repair. An example of the flexibility in a bolt and mesh system subjected to large ground displacement is the rock reinforcement used in a deep gold mine in Zambia (20). In that case, mined openings in rock, highly fractured as a result of rockbursts, have been maintained with a system of fully-grouted steel dowels (rockbolts), wire mesh, and steel cable lacing stretched across the tunnel walls in a diamond pattern between the dowels. During large ground displacements this structural system provides sufficient supporting pressure to confine the rock mass, thereby maintaining its self-supporting capacity.

B. Lining Systems

Lining systems, especially in civil tunnels usually are designed to fulfill another function, such as water conveyance or transportation, in addition to the function of providing long-term ground support. These linings are often reinforced cast-in-place concrete, which is considered too stiff and unyielding to accommodate fault movement. In this regard, for design of the Bay Area Rapid Transit tunnel through the Berkeley Hills, where displacement on the Hayward fault was a consideration, a flexible lining design was implemented by keeping the tunnel lining as thin as practicable (21).

A more elaborate flexible lining design has been proposed by Desai, et al., (22). Their design uses a conduit or pipe, placed within the drift and surrounded with a low modulus backpacking. The design uses segmented precast pipe with joints configured to accommodate extentional and compressional strains. The pipe maintains the function of the opening and is protected from significant damage because discrete fault displacements are not transmitted by the surrounding backpacking. Instead, lateral and longitudinal forces resulting from the faulting are distributed along the enclosed pipe and absorbed by deformation of the segmented pipe.

As in the case of the segmented pipe-in-tunnel design, a drift lining can be designed with flexible joints to accommodate fault displacement and avoid undue damage to the lining. Frame (23) has described a lining design for the tunnel outlet at the Coyote Dam, which is constructed across the Calaveras fault zone. A section of lining 56.5 meters long was designed to withstand expected displacements on a fault interpreted to be subordinate to the Calaveras fault. The lining was designed for an estimated 0.2-meter single event displacement using articulated joints placed at 3-meter centers, each designed to withstand a 0.3 meter displacement in any direction without failure.

IV. IMPLEMENTATION OF THE NRC STAFF TECHNICAL POSITION ON SEISMIC DESIGN FOR TYPE I FAULTING FOR SEISMIC DESIGN OF YUCCA MOUNTAIN

The NRC Staff Technical Position (STP) on an acceptable process and criteria to identify Type I faults (2) describes a two-step process: 1) identification of faults that are subject to displacement, and 2) assessment of whether such faults may affect repository design and/or performance. Specific criteria and guidance are given in the STP for implementing the first step of the process: movement during the Quaternary Period. To implement the second step, the STP states that fault length should be used as a measure to assess the possible affects of fault displacement on repository design or performance. This suggested implementation of the second step implies acceptance of a site-specific relationship between the length of a fault and displacement in a single earthquake such as the general relationship given by Wells and Coppersmith (25). The STP further recommends that the DOE should develop technically defensible criteria based on fault length for application at the Yucca Mountain site to identify specific faults or fault zones among those that have Quarternary displacement, that may affect repository design and/or performance.

Site characterization studies performed to date have shown that individual displacements on faults in the Yucca Mountain GROA during the Quarternary Period have been small, typically less than 200 cm during the past 100 - 200 ka (24). Rates of movement are very low, in the range of 10^{-2} mm/yr to 10^{-3} mm/yr, and average earthquake recurrence intervals are 20,000 to more than 100,000 years (24). In addition, consistent with the results reported by Wells and Coppersmith (25) based on their analysis of the world-wide data set on fault displacement versus fault length, the displacement per event for the faults at Yucca Mountain varies strongly as a function of fault length (24). While characterization of the faults in the Yucca Mountain GROA has not been completed at this time, data currently available relating fault displacement to length of faulting indicate that the site-specific investigations will provide a basis for implementating Step 2 of the two-step process given in NUREG-1451, for identifying Type I faults.

V CRITERIA FOR IMPLEMENTATION OF FAULT DISPLACEMENT DESIGN

The DOE's design considerations to accommodate fault displacements follow the intent of NRC's Staff Technical Position (1). The STP specifically recognizes that the presence of Type I faults inside the GROA does not, by itself, disqualify a candidate site for a geologic repository. However, strong guidance is given to avoid Type I faults where avoidance can reasonably be achieved. Thus, consistent with the STP, for SSCs that have radiological safety importance the principal fault displacement design action will be fault avoidance. SSCs that have radiological safety importance will be placed in performance categories three and four (PC-3 and PC-4 (3, 4, 5, 6)). Fault avoidance for PC-3 and PC-4 SSCs will be accomplished to the extent reasonably achievable through the design layout of the facility. However, also consistent with the STP, the DOE recognizes that it likely will not be reasonably feasible to avoid all Type I faults. This is particularly the case for spatially extended SSCs. For such cases, reasonable assurance of safe performance will be demonstrated by design of those SSCs to withstand the expected fault displacement hazards equal to their established seismic safety performance goal (3, 4, 5).

A. Criteria for Fault Avoidance

For the purpose of developing specific design requirements to meet the design criteria, the facility SSCs will be divided into two groups: those that are spatially compact or clustered and those that are spatially extended. For clustered SSCs, the design requirement will be fault avoidance, except: a) when a compelling reason exists (e.g., fault avoidance reduces overall system safety), and it can be conservatively demonstrated that the SSC can withstand the fault displacement corresponding to the SSC's established seismic safety performance goal; or b) when it can be demonstrated that the radiological consequences of SSC failure (due to fault displacement loads) are well within acceptance criteria. For spatially extended SSCs, to the extent reasonably feasible, the design requirement will be fault avoidance. When fault avoidance is not reasonably achievable, design criteria and procedures will be implemented to reasonably assure that the SSC will perform its safety function, if subjected to the design basis fault displacement.

Spatially clustered SSCs will not be placed across Type I faults except when there are compelling reasons to do so, as discussed in the previous paragraph. In addition, the following conservative layout guidelines will be implemented.

i) PC-4 and PC-3 (3, 4) SSCs that are spatially extended in a long and narrow configuration (drifts, ramps, utility lines, conduits, ventilation ducts, buried pipes) will not be placed coincident with the trace of a Type I fault within its set-back distance. The set-back distance of a fault is the distance from the main fault trace that would be subjected to unacceptable displacement due to a displacement event on the main fault. When the set-back criterion is not reasonably achievable because of practical layout requirements, the affected SSC will be designed for fault displacement hazard equal to its established seismic safety performance goal.

ii) When practical layout requirements make it necessary to place spatially extended SSCs across a Type I fault, the layout will be configured such that the SSC crosses the fault trace at a angle as near normal as can be achieved consistent with the overall system demands.

Because of the significant variation in fault behavior that governs the width of a fault and the importance of specific characteristics of a SSC, the required set-back distance from a fault, when fault avoidance is the appropriate design action, will be highly fault-specific. For this reason no generally applicable generic criteria are given. It will be necessary, therefore, to determine specific set-back distances during the final design of the facility following completion of appropriately detailed evaluations of faults within the Geologic Repository Operations Area. Some guidance for determining fault set-back can be obtained from engineering evaluations of expected responses of SSCs to fault displacement. Analysis performed by Kennedy and Kincaid (26) have shown that total strain induced in a pipeline by fault displacement decreases by about 60 % at a distance of 20 feet from the locus of displacement and by about 80% at a distance of 100 feet.

B. Criteria for Fault Displacement Design

As stated in the introduction to this paper, approaches to provide assurance of safe performance of SSCs with respect to fault displacement fall into three categories: fault avoidance, geotechnical engineering isolation techniques, and structural engineering design to increase structural ductility or to provide for structural modularization. The appropriate approach or combination of approaches will be SSC and fault-specific. As a general requirement, SSCs will be designed for loads determined by a design basis fault displacement, d, corresponding to the SSC and fault-specific performance goal P_F (4, 6).

For SSCs in PC-3 or PC-4, the following fault displacement design actions will be implemented.

1. Near-Surface Buried Piping

Piping is highly ductile; consequently, piping systems are able to withstand significant displacements causing large strains, without loss of function (15, 16). Generally piping performance when subjected to fault displacement will depend on whether tensile or compressive distortion is imposed on it. Analyses and observed performance shows that piping is able to withstand significantly larger tensile strains than compressive strains. Whether the piping deforms in tension or compression in a fault displacement depends on the angle of the piping with respect to the faulting direction at the fault crossing. Therefore, whenever possible, pipeline alignment at a fault crossing will be such that the piping will be subjected to tension. Alignments which would place the piping in compression will be avoided whenever reasonably possible.

Acceptable analysis procedures, for the design of piping systems for fault displacement are given in ASCE (16). These analysis procedures together with the design acceptance criteria described in section VI of this paper and in reference 3 will be followed for the fault displacement design of the Yucca Mountain piping system.

2. Ventilation Shafts and Ducts

Ventilation shafts and ducts as well as the underground openings, will control the movement of air through the facility, its distribution, amount and quality. The NRC's regulation, 10 CFR 60.133(g)(3) requires that the underground facility ventilation system must separate the ventilation of the excavation and waste emplacement areas. A final ventilation design concept has not been adopted at this time. However, two fully independent ventilation systems that have no operational impacts on each other, are favored because of safety considerations. According to the current conceptual design given in the Advanced Conceptual Design Summary Report (27), this will require two exhaust shafts with inside diameters on the order of 6.0 meters.

For ventilation ducts crossing Type I faults, the design action will be installation of flexible connections on the duct on each side of the fault to accommodate the design basis displacement d, corresponding to P_F (4, 6). The flexible connection will be conservatively designed to provide reasonable assurance that the ventilation duct will retain its function following the design basis fault displacement according to the design acceptance criteria given in reference 3 and in section VI of this paper.

When practical repository lay-out considerations require that a ventilation shaft be placed across a Type I fault, the design basis fault displacement will be accommodated by adding a flexible metal liner along the sector crossing the fault. The flexible metal liner will span a distance on either side of the fault such that reasonable assurance is provided that the shaft will maintain its function if subjected to the design basis fault displacement.

3. Surface Facilities

Analyses and observations have shown that well-designed embedded structures can withstand vibratory ground motion and co-seismic fault displacement without loss of safety function (8, 9, 10, 11, 12, 13, 14). Nevertheless, because of economic and regulatory efficiency considerations, the primary design action for the Yucca Mountain GROA surface facility will be fault avoidance. When practical facility layout considerations make it necessary to place a surface facility primary structure across a Type I fault, the following design guidelines will be used together with the acceptance criteria given in section VI of this paper.

a. Surface facility primary structures containing PC-4 or PC-3 SSCs, that are located within the control width of a Type I fault will be designed such that when the structure is subjected to the design basis fault displacement, there is reasonable assurance that it will continue to perform its safety function (i. e., confinement function). The analysis will take due account of the structure's design and layout features including its embedment and subsystems. In addition, the analysis will assume shipping cask drops from a crane or rail inside the surface structure.

b. For vibratory ground motion the seismic design guidelines and criteria described by Hossain (4) will be used. For combined vibratory ground motion loads and fault displacement loads design strain limits will be set sufficiently conservative to assure safe performance.

4. Ground Supports for Underground Openings

Ground supports for underground openings may consist of tunnel linings, rock bolts and other engineered actions to provide the desired stability and safety performance. Experience has shown that damage caused by even relatively large fault displacements through underground openings can be repaired and rehabilitated relatively easily when necessary (3, 5, 7). Investigations of faulting in the GROA to date show that fault displacements are small and intervals between displacement recurrence ranges from about 20,000 years to more than 100,000 years (24). Generally tunnels design practice has been established for higher recurrence rate events. Nevertheless, the general practices of the tunneling industry have been adopted for analysis and design or the Yucca Mountain SSCs for fault displacement (3, 5). Actions that will be taken to assure safe performance at crossings of Type I faults consist of:

a. excavation of an oversize section through the fault zone and use of flexible support systems; or

b. incorporation of a flexible coupling, when the opening is lined.

For underground openings, PC-4 or PC-3 SSC ground support systems will be designed to accommodate design basis fault displacements without loss of intended safety function. PC- 2 and PC-1 underground openings are considered to require no specific additional ground support design to accommodate fault displacement. For these SSCs, inspection and rehabilitation will be sufficient to reasonably assure maintenance of intended function (3, 5).

Usually faults also are zones of poor rock quality that require enhanced ground support compared to un-faulted or intact rock. The ground support systems for any zones of poor rock quality associated with fault crossings will be designed tó reasonably assure safe performance with no degradation of the safety performance of underground SSCs.

In addition to implementing the above design provisions, instrumentation will be designed and installed at locations where PC-4 or PC-3 (3, 5) SSCs cross faults to monitor any movement that may occur during the preclosure period.

VI. DESIGN ACCEPTANCE CRITERIA FOR SSCs SUBJECTED TO FAULT DISPLACEMENT LOADS

When displacements occur at a fault, an SSC straddling the fault line tends to resist the fault movement. As a result, the SSC is subjected to fault displacement loads. These loads depend on the magnitude and direction of the fault movement as well as on the ease with which the two segments of the SSC on two sides of the fault line can move relative to each other. The latter depends on:

i. the stiffness (or flexibility) of the SSC, especially in the vicinity of the fault line,

ii. the stiffness (or flexibility) of the ground around the buried segment or foundation of the SSC, especially in the vicinity of he fault line, and,

iii. the configuration of the SSC.

Once the design basis fault displacements are determined, the resulting loads (or stresses) and deformations (or strains) in the SSC will be calculated using analytical models that will consider the above three parameters. When similar loads/stresses and deformations/strains are calculated for vibratory ground motion, as described in references 3, 4, 5, it is customary to use stress-based acceptance criteria to establish design adequacy, assuming essentially linear elastic behavior, which is the basis for industry codes and standards. Unlike vibratory ground motion loads, however, fault displacement loads are generally localized, and often cause inelastic response of SSCs especially in the vicinity of the fault line(unless the SSC and the ground medium are very flexible, in which case the SSC can undergo large deformation staying within elastic limits). For this reason, it is appropriate to use strain-based acceptance criteria to establish the design adequacy of SSCs subjected to fault displacement loads.

In establishing such strain-based acceptance criteria for the Yucca Mountain Repository facilities, nuclear power plant and other industry experiences with the use of similar strain-based criteria will be used. Examples are the strain criteria used for designing pipe rupture restraint systems and for designing SSCs subjected to accidental impassive and impulsive loads such as those resulting from tornado missiles, turbine missiles, aircraft crash, cask drop, reactor vessel head drop, and others that may be applicable (28). Some similarities also exist between localized inelastic response of SSCs when subjected to fault displacement loads and localized stresses well beyond linear elastic limit of materials permitted by the ASME Boiler and Pressure Vessel Code.

As has been stated in section II above, when fault avoidance cannot be reasonably achieved, PC-3 and PC-4 (3, 4) SSCs will be designed for fault displacements corresponding to a hazard exceedance probability equal to the seismic safety performance goal P_F (3,6) established for the SSC. In other words, if there were no uncertainty in the fragility of the SSC, it could be designed to incipient failure (at P_F-based loads) and it would still achieve its seismic safety performance goal. Because of uncertainties in the fragilities of SSCs, however, the design acceptance criteria for fault displacement loads will not permit strain levels up to the ultimate or failure strain limit of the material. Instead, the limiting strain will be determined by considering the parameters that can influence uncertainties in the SSC fragility. Explicitly, these are:

(a) the configuration of the SSC;

(b) the SSC failure mode;

(c) the SSC material characteristics (brittle versus ductile);

(d) the stiffness of the SSC; and

(e) the stiffness of the ground material in the vicinity of the fault.

Considering these parameters, strain limits will be established on a case-by-case basis to provide reasonable assurance that the seismic safety goal established for the SSC will be achieved.

VII. CONCLUSIONS

Analysis and limited experience indicate that structures, systems and components of the proposed Yucca Mountain facility can be designed to safely withstand loads imposed by fault displacement and meet the proclosure safety performance objectives of 10 CFR Part 60. Design approaches fall into three general categories: fault avoidance, geotechnical engineering to achieve isolation of a SSC, and structural engineering design to increase structural ductility or to provide structural modularization. It is expected that all of these approaches will be used in the desing of the Yucca Mountain facility. Fault avoidance will be the primary design approace for SSCs that have radiological safety significance (PC-3 and PC-4). When fault avoidance is not reasonably feasible, SSCs in PC-3 and PC-4 will be designed for fault diaplacements that correspond to a hazard frequency equal to the established seismic safety performance goal, P_F.

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