RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

3/27/2014

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.:	**NO. 960-6709 REVISION 0**
SRP SECTION:	**03.07.02 – Seismic System Analysis**
APPLICATION SECTION:	**3.7.2**
DATE OF RAI ISSUE:	**09/24/2012**

QUESTION NO. 03.07.02-217:

Section 4.2.1 of MHI's TR MUAP-12002 (R0), "Sliding Evaluation and Results," describes the selection of the static and kinetic (sliding) coefficients of friction. To assist the staff in evaluating whether appropriate static and kinetic coefficient of friction values are utilized in accordance with the guidance in SRP Section 3.8.5, the staff requests the applicant to provide the following additional information:

a) Section 4.2.1 of the TR states, "The governing friction occurs between the mud mat and the underlying granular soil where a thin soil layer exists that is interlocked with the bottom of the mud mat." The applicant is requested to provide the technical basis and justification for the conclusion that the sliding interface would not be at the concrete to soil interface.

b) The TR indicates that any fine grain materials within a few feet below the basemat will be replaced by engineered fill. Engineered fill will be specified in the DCD as a well drained granular backfill with a minimum friction angle of $\Phi = 35°$. The applicant states that the minimum angle of internal friction will be specified in DCD Table 2.0-1 as a site requirement.

   The staff notes that, regardless whether materials below the basemat are replaced by engineered fill, the DCD needs to specify the minimum angle of internal friction. Therefore, the applicant is requested to confirm that the minimum angle of internal friction for the in-situ soil, and any engineered fill, will be specified in DCD Tier 2, Section 2; and that in-situ soil will also be specified in DCD Tier 1.

c) Another potential sliding interface is at the location of any waterproofing material (e.g., waterproofing material between the mud mat and soil or between the basemat and mud mat).

   Therefore, the applicant is requested to explain where waterproofing material is used; the type of waterproofing material; the coefficient of friction of the waterproofing material with respect to the adjacent material; and the basis for the coefficient of friction.

d) The TR indicates that the cold joint at the mud mat to bottom of foundation contact will be "raked" with a very rough surface (minimum amplitude greater than ¼ inch - as recommended in the Commentary to ACI 349-06 to maintain a minimum friction coefficient of 0.7. The applicant is requested to include this commitment in the DCD.

e) The kinetic coefficient of friction used for the sliding stability analysis is given as 0.5 for all subgrades. The value of the kinetic coefficient of friction is based on laboratory soil tests with samples from seven different types of sands. The applicant is requested to confirm that the kinetic coefficient of friction used for the design basis sliding stability analysis bounds the types of soils and soil properties/conditions considered for the US-APWR standard design.

f) Reference 13 in the TR could not be located. To complete its review, the staff requests the applicant to submit a copy of Reference 13: "Constant Volume Cyclic Simple Shear Testing," Proceedings of the 2nd International Conference on Microzonation, San Francisco, CA, Finn, W.D.L., Laid, Y.P. and Bhatia, S.K., pg. 839-851, 1978

ANSWER:

As discussed with the Nuclear Regulatory Commission (NRC) staff during the Design Certification Document (DCD) Tier 2, Section 3.7.1, 3.7.2, and 3.7.3 Audit conducted in September 23-27, 2013, This answer revises and replaces the previous MHI answer that was transmitted by Letter UAP-HF-12292 (ML12356A069).

a) The concrete-soil interface discussed in Section 4.4 of the Technical Report MUAP-12002, Rev. 1, is the interface between the mud mat and granular soil. As explained in the Technical Report, for concrete that is placed directly on the granular soil and penetrates between the soil grains, the actual concrete soil interface is not smooth and the friction failure is forced to take place in the soil immediately below the concrete. This is reflected by the fact that the recommended friction angle at contact between mass concrete and granular soil is the internal friction angle of the soil, ϕ (see Reference 17 of the Technical Report).

b) The following requirements will be specified in Tier 1 and Tier 2 of the Design Control Document (DCD):

   The soil subgrade below basemat shall have a minimum angle of internal friction angle of 35°. If the friction angle of 35° cannot be demonstrated (such as for a clay material), the COL Applicant must demonstrate a minimum kinetic friction coefficient of 0.5 at the base of the Reactor Building Complex and of the Turbine Building. Otherwise, the COL Applicant must demonstrate sliding stability through site specific analysis.

c) No waterproofing membrane will be used below the basemats of US-APWR structures. Required concrete waterproofing will be ensured by using appropriate concrete.

d) DCD Subsection 3.8.5.5.2 is revised to include the commitment to rake the concrete to a full amplitude of 0.25 in. to achieve a coefficient of friction of 1.0, per American Concrete Institute (ACI) 349-06, Section 11.7.9, between the fill concrete and the basemat.

e) The kinetic friction coefficient for concrete-to-concrete and concrete-to-rock interfaces are discussed in Section 4.4 of Technical Report MUAP-12002, Rev. 1, based on test results reported in the literature. For interfaces involving soil, granular soils are

discussed only in relation to friction coefficients used for sliding analysis. Moreover, any friction failure at the mud-mat granular soil interface occurs within the soil mass, as explained in the Answer to Question 217a and in Section 4.4 of Technical Report MUAP 12002, Rev. 1. The special case when a mud-mat would be placed on cohesive soil is dealt with by the special requirements in the DCD discussed in the Answer to Question 217b and by additional updates to Section 4.4 of Technical Report MUAP 12002, Rev. 1, regarding clay subgrades. Therefore, the laboratory test results discussed in this answer refer only to granular soil.

The internal friction angle is the parameter of interest for assessing the shear strength properties of granular soil. The soils and soil property conditions considered for assessing friction coefficients include granular soils with shear wave velocities equal to, or larger than, 270 m/sec., i.e., dense granular soils, either natural soils or engineered fills. As discussed in Section 4.4 of Technical Report MUAP-12002, Rev. 1, the soil samples used in the laboratory soil tests described in Reference 20 of the Technical Report include various types of granular soils with friction angles between 28° and 48°, which envelop the range of friction angles for dense granular soils (either natural or engineered fill) considered for the US-APWR standard design.

f) See the requested reference attached to this response.

Impact on DCD

The DCD will be revised as shown in Attachment 1.

Impact on R-COLA

There is no impact on the R-COLA.

Impact on PRA

There is no impact on the PRA.

Impact on Technical/Topical Report

Technical Report MUAP 12002, Rev. 1 section 4.4 will be revised as shown in Attachment 2.

This completes MHI's response to the NRC's question.

Attachment 1

Table 2.1-1 Key Site Parameters
(Sheet 7 of 8)

Hydrologic Engineering	
Parameter Description	**Parameter Value**
Maximum flood (or tsunami) level	1 ft below plant grade
Maximum rainfall rate (hourly)	19.4 in/hr for seismic category I/II structures
Maximum rainfall rate (short-term)	6.3 in/5 min for seismic category I/II structures
Maximum groundwater level	1 ft. below plant grade
Geology, Seismology, and Geotechnical Engineering	
Parameter Description	**Parameter Value**
Maximum slope for foundation-bearing stratum	20˚ from horizontal in untruncated strata
Safe-shutdown earthquake (SSE) ground motion	0.3 g peak ground acceleration
SSE (certified seismic design) horizontal ground response spectra	Regulatory Guide (RG) 1.60, enhanced spectra in high frequency range (See Figure 2.1-1)
SSE (certified seismic design) vertical ground response spectra	RG 1.60, enhanced spectra in high frequency range (See Figure 2.1-2)
Potential for surface tectonic deformation at site	None within the EAB
Subsurface stability – minimum allowable static bearing capacity	15,000 lb/ft^2
Subsurface stability – minimum allowable dynamic bearing capacity, normal conditions plus SSE	35,000 lb/ft^2
Minimum factors of safety for bearing capacity without justification (16)	FS = 2.5 - for static bearing capacity FS = 2.0 - for dynamic bearing capacity
Subsurface stability – minimum shear wave velocity at SSE input at ground surface	1,000 ft/s
Subsurface stability – liquefaction potential	None (for seismic category I structures)
Minimum angle of internal friction for engineered fill ~~and~~or natural in-situ granular soil subgrades beneath the basemat	35˚
~~Presence of fine-grained materials, i.e., silts and clays classified as ML, CL, MH, CH in the Unified Soil Classification System, within 6 in. of bottom of R/B Complex and T/B basemat~~	~~Not Permitted~~
Maximum moist unit weight for engineered fill or natural in-situ granular soil at the sides of the foundation	125 pounds per cubic foot
Maximum angle of internal friction for engineered fill or natural in-situ granular soil at the sides of the foundation	35˚
Total settlement of R/B complex foundation during construction and operational life(14)(15)	9.0 in.

DCD_03.07.03-12

DCD_03.07.02-217

DCD_03.07.03-12

3.8.5.5 Structural Acceptance Criteria

Structural acceptance criteria are discussed in detail in Subsections 3.8.1.5 and 3.8.4.5. The design soil conditions are as provided in Section 2.5 and Subsection 3.7.1.3. The COL Applicant is to ensure that the design parameters listed in Chapter 2, Table 2.0-1, envelope the site-specific conditions.

Seismic category I and II structures are evaluated against acceptance criteria with respect to overturning, sliding, and flotation stability. The load combinations applicable to the stability evaluations are specified in Table 3.8.5-1. For each of the specified load combinations, the acceptance criterion for the overturning, sliding, and flotation stability evaluations is the minimum factor of safety identified in Table 3.8.5-1. The design methodology and requirements for calculating the factors of safety are described further in Subsections 3.8.5.5 below. The minimum calculated factor of safety for each load combination considered in the stability evaluations is presented in Table 3.8.5-6. Site-specific stability evaluations are required to be performed by the COL Applicant for standard plant seismic category I and II structures to confirm the minimum required values in Table 3.8.5-1, unless the COL Applicant can demonstrate that the site specific conditions for evaluating stability are enveloped by the standard plant design. The COL Applicant is to also provide the factors of safety for site-specific seismic category I structures ~~in Table 3.8.5-6~~ based on the methodology and acceptance criteria presented in Subsection 3.8.5.5. DCD_03.07.02-217

3.8.5.5.1 Overturning Acceptance Criteria

The factor of safety against overturning is identified as the ratio of the moment resisting overturning (M_r) divided by the overturning moment (M_o). Therefore,

$$FS_o = [\, M_r / M_o \,] \text{, not less than } FS_{ot} \text{ as determined from Table 3.8.5-1.}$$

where

FS_o = Structure factor of safety against overturning by the maximum design basis severe wind, tornado, hurricane, or earthquake load.

M_r = Resisting moment provided by the dead load of the structure, minus the buoyant force created by the design ground water table.

Passive earth pressure is not considered for overturning stability.

M_o = Overturning moment caused by the maximum design basis severe wind, tornado, hurricane or earthquake load.

The calculated minimum factors of safety presented in Table 3.8.5-6 show that the SSE load combination governs over wind and tornado load combinations for evaluating overturning stability. The standard plant SSE overturning stability evaluations are performed using the dynamic FE models and the seismic driving forces/moments obtained from the site independent SSI analyses. The SSI analyses are conducted separately for each earthquake direction. The earthquake responses from the separate SSI analyses are then applied simultaneously to evaluate overturning stability. The SSE

The development and calibration of the lump mass stick model for the R/B complex are presented in Appendix A of Technical Report MUAP-12002. The lump mass stick model was calibrated based on the FE model by matching the dynamic properties, and was subsequently fine tuned and validated by comparing the calculated maximum sliding obtained with the LMSM with the corresponding values calculated with the FE model. Further verifications were performed on (1) comparison of overall seismic demands, and (2) comparisons of base reactions between the lump mass stick model with fixed base and the FE model used in the SSI analyses. These lump mass stick models are used for screening and are validated only for sliding analyses. The lump mass stick models are not appropriate for inferring any structural responses other than seismic induced sliding.

The standard plant non-linear sliding stability calculations use a friction coefficient of 0.5, which is a kinetic coefficient of friction. To ensure an adequate friction coefficient is achieved, the following requirements apply to the subgrade conditions at the plant site:

- A minimum 35° internal friction angle is required for natural (in-situ) or engineered ~~granular~~ soil materials at the basemat - sub grade interface. If a friction angle of 35° cannot be demonstrated (such as for clay material), the COL Applicant must demonstrate a minimum Kinetic friction coefficient of 0.5 at the base of the R/B complex and the T/B. Otherwise, the COL applicant must demonstrate sliding stability through site specific analysis. DCD_03.07.02-217

- ~~Fine-grained materials i.e., silts and clays classified as ML, CL, MH, CH in the Unified Soil Classification System immediately below the basemat will be replaced by granular backfill having a minimum 35° internal friction angle. The backfill will~~ If a layer of backfill is placed below the basemat, it shall be specified to be 4 to 6 inches thick with a maximum of 1 foot. This fill will be topped with a 3 to 4 inch mud mat. This layer must be made of well graded clean sand and/or gravel with at most 5% fines. The degree of compaction is determined to ensure that the dynamic properties of the backfill are similar to that of the native soil. Backfill placed below the R/B Complex and the T/B basemats shall be compacted to a dry density of at least 95% of the maximum dry density obtained from ASTM D1557 (Reference 3.8-84), to within 3 percent of its optimum moisture content. At least one field density test shall be performed for every 200 cubic yards of backfill placed.

  The COL applicant shall verify that: (1) the degree of compaction for the backfill placed beneath foundation has to be analyzed by field density tests only, since shear wave velocity or SPT measurements cannot be performed for such a thin layer of soil and (2) the friction resistance requirement, specified as a friction angle of at least 35°, is met.

  These requirements apply to backfill placed under the mats of the R/B Complex and the T/B to ensure that the dynamic properties are similar to the native soil.

- At basemat or mud mat interfaces with rock, the rock surface must be cleaned, with fissures and fractures filled in, as specified in a construction specification.

- The interface between the basemat concrete and the top surface of the mud mat must be clean and free of laitance. ~~When a coefficient of friction > 0.6 is used in calculating sliding resistance F_s, r~~Roughening of mud mat is required per criteria given in Section 11.7.9 of ACI 349-06 (Reference 3.8-8). ~~If a coefficient of friction ≤ 0.6 is used by the COL Applicant in a pseudo-static sliding stability analysis, roughening of mud mat is not required.~~ DCD_03.07.02-217

Unless the COL Applicant can demonstrate by means of pseudo-static analysis that seismic induced sliding does not occur and that a safety factor against sliding ≥ 1.1 is achieved, site-specific seismic sliding stability analyses is to be performed using the seismic sliding stability analysis methodology described in Technical Report MUAP-12002 (Reference 3.8-82). If non-linear sliding analysis is performed, the COL Applicant is to demonstrate that resulting sliding is ≤ 0.75 in. for the R/B complex and ≤ 0.20 for the T/B.

3.8.5.5.3 Flotation Acceptance Criteria

The factor of safety against flotation is identified as the ratio of the total dead load of the structure including basemat (D_r) divided by the buoyant force (F_b). Therefore,

$FS_f = D_r / F_b$, not less than FS_{fl} as determined from Table 3.8.5-1.

where

FS_f = Structure factor of safety against flotation by the maximum design basis flood or ground water table.

D_r = Total dead load of the structure including basemat.

F_b = Buoyant force caused by the design basis flood or high ground water table, whichever is greater.

3.8.5.6 Materials, Quality Control, and Special Construction Techniques

Subsection 3.8.4.6 describes the materials, quality control, and special construction techniques applicable to seismic category I basemats, including water control structures and below-grade concrete walls and basemat. Subsection 3.8.1.7 provides testing and surveillance requirements relating to the R/B complex basemat.

3.8.5.7 Testing and Inservice Inspection Requirements

Subsection 3.8.4.7 identifies the testing and inservice surveillances applicable to seismic category I basemats, including water control structures and below-grade concrete walls and basemats. Subsection 3.8.1.7 also identifies testing and surveillance requirements relating to concrete crack observations of the R/B complex basemat. Monitoring and maintenance of seismic category I basemats is performed in accordance with RG 1.160 (Reference 3.8-30) to ensure that design basis assumptions and margins are not unacceptably degraded.

COL 3.8(26)	*Actual total and differential settlements are dependent on site-specific conditions (e.g., soil variability, construction sequence and schedule (including basemat stiffening), loading conditions, excavation plans, and dewatering plans). The COL Applicant is to perform settlement analysis for the specific site, the in-situ soil properties, and for the specific construction schedule to verify that the site-specific total and differential settlements, and tilt, are bounded by the settlements and tilt in Table 2.0-1 of Chapter 2. If the site-specific settlements and tilt are bounded by the values in Table 2.0-1, detailed site-specific stress and gap closure verifications are not required with regard to settlement and tilt effects.*
COL 3.8(27)	*The COL Applicant is to specify normal operating thermal loads for site-specific structures, as applicable.*
COL 3.8(28)	*The COL Applicant is to specify concrete strength utilized in non-standard plant seismic category I structures.*
COL 3.8(29)	*The COL Applicant is to provide design and analysis procedures for the ESWPT, UHSRS, and PSFSVs.*
COL 3.8(30)	*When a coefficient of friction > 0.6 is used in calculating sliding resistance F_s, roughening of mud mat is required per criteria given in Section 11.7.9 of ACI 349-06 (Reference 3.8-8). If a coefficient of friction $\leq$ 0.6 is used by the COL Applicant in a pseudo-static sliding stability analysis, roughening of mud mat is not required.*
COL 3.8(31)	*Site-specific stability evaluations are required to be performed by the COL Applicant for standard plant seismic category I and II structures to confirm the minimum required values in Table 3.8.5-1, unless the COL Applicant can demonstrate that the site-specific conditions for evaluating stability are enveloped by the standard plant design. The COL Applicant is to also provide the factors of safety for site-specific seismic category I structures ~~in Table 3.8.5-6~~ based on the methodology and acceptance criteria presented in Subsection 3.8.5.5.* DCD_03.07.02-217
COL 3.8(32)	*Unless the COL Applicant can demonstrate by means of pseudo-static analysis that seismic induced sliding does not occur and that a safety factor against sliding $\geq$ 1.1 is achieved, site-specific seismic sliding stability analyses is to be performed using the seismic sliding stability analysis methodology described in Technical Report MUAP-12002 (Reference 3.8-82). If non-linear sliding analysis is performed, the COL Applicant is to demonstrate that resulting sliding is $\leq$ 0.75 in. for the R/B complex and $\leq$ 0.20 for the T/B.*
COL 3.8(33)	*The COL applicant is to provide detailed construction and inspection plans and documents in accordance with MUAP-12006.*

4.4 Subgrade Properties

Six SPs, described in Reference 5, are considered for the nonlinear sliding analyses. Subgrade properties, including soil layering, as well as stiffness and damping for each layer, are input parameters for the SSI analyses that provide the ground accelerations at the basemat-subgrade level, accounting for the effect of the soil profiles on seismic accelerations, as outlined in Section 4.5.2.

The most important subgrade parameter in sliding analysis is the coefficient of friction at the basemat-subgrade interface. This friction coefficient has different values for the case when the structure has not started sliding (static friction coefficient, μ_s) and for the case when the structure is already sliding (kinetic friction coefficient, μ_k). Values of these coefficients that are appropriate for the Standard Plant design are discussed below.

The kinetic friction coefficient, μ_k = 0.50, is conservatively used throughout the nonlinear sliding analyses.

Relative sliding, due to exceedance of contact friction forces, may occur either (1) between the mud mat (mass concrete placed directly on subgrade) and soil or rock, or (2) between the bottom of the foundation (concrete mat) and the mud mat, or (3) within the subgrade, below the interface with the basemat. These interfaces are discussed below for various types of subgrade. It is also mentioned that no waterproofing membrane will be used below the basemats of the structures, and required concrete waterproofing will be ensured by using appropriate concrete admixtures.

<u>Static friction coefficient, μ_s between the bottom of foundation and mud mat</u>

The cold joint at the mud mat to bottom of foundation contact is a mechanical interface since the mud mat will not be smooth. It will be “raked” to a very rough surface (minimum amplitude greater than ¼ inch - as recommended in ACI 349-06, Reference 15, paragraph 11.7.9) to maintain a minimum friction coefficient of 1.0 for both dry and wet surfaces. Based on laboratory test results from over 150 specimens, the Electric Power Research Institute (EPRI) (Reference 16) indicates a lower bound of 57 degrees for the peak friction angle at the concrete-to-concrete contact for cold joints.

<u>Static friction coefficient, μ_s (rock subgrades)</u>:

The static friction coefficient characterizes the shear strength of the interface before sliding occurs. Based on Reference 17, μ_s between mass concrete and various subgrade materials corresponds to an angle of friction (Φ) of 35° for rock and is equal to the friction angle at failure for soils. An angle of friction of 35° is equivalent to a static friction coefficient μ_s = 0.7.

<u>Static friction coefficient, μ_s (granular soil subgrades)</u>:

Based on correlations in the literature (see Reference 17), granular soils with properties corresponding to the requirements in Reference 5, namely with shear wave velocities V_S > 270 m/s, have effective friction angles, Φ, of approximately 40°. The governing friction occurs between the mud mat and the underlying granular soil where a thin soil layer exists that is interlocked with the bottom of the mud mat. Upon impending sliding conditions, this layer is constrained to move together with the mud mat. Therefore, sliding of mass concrete placed directly on granular soil is a shear failure phenomenon (case 3 mentioned at the beginning of this section, with sliding through the subgrade) and the “friction coefficient” is an expression of the shear strength of the soil. A conservative value of Φ = 35°, corresponding to a friction coefficient μ_s = 0.7, is considered for this type of soil. In order to provide a suitable subgrade material, the soil should not include a significant amount of fines and be compacted to an adequate relative density (at least 65%, corresponding to dense sand) before the placement of the mud mat.

Kinetic friction coefficient, μ_k (rock and granular soil subgrades):

The kinetic friction coefficient characterizes the shear strength of the interface during sliding. This shear strength is also termed as “residual strength”. Based on results of a large number of laboratory and full scale tests (a comprehensive review is presented in Reference 18), the residual strength friction angle at concrete-to-concrete and concrete-to-rock interfaces exceeds 30°, corresponding to kinetic friction coefficients, $\mu_k > 0.57$, for both dry and wet surfaces.

The residual friction angle for granular soils is also known as the constant volume friction angle or the steady state friction angle (e.g., Reference 19). Been and Jefferies (Reference 20) report values of the residual friction angle based on a large number of laboratory soil tests with samples from seven different types of sand. Most values range between 30° and 32°, with extreme values of 27° and 35°, all yielding kinetic friction coefficients, $\mu_k > 0.5$. The soils and soil property conditions considered in this TeR for assessing the residual friction angles, and therefore the friction coefficients, include granular soils with shear wave velocities equal to or larger than 270 m/s, i.e., dense granular soils, either natural soils or engineered fills. The soil samples used in the laboratory soil tests described in Reference 20 include various types of granular soils with friction angles between 28° and 48°, which envelop the range of friction angles for dense granular soils (either natural, or engineered fill) considered for the US-APWR standard design.

Static and Kinetic friction coefficients for clay subgrades:

A minimum friction angle of 35°or a minimum kinetic friction coefficient $\mu_k = 0.5$ must be demonstrated by the COL Applicant for clay subgrades in contact with the basemats of the R/B complex and the T/B. If this cannot be demonstrated, COL applicant must either: (1) demonstrate sliding stability through site specific analysis, or (2) replace the fine grained soil immediately below the basemat by engineered fill. The engineered fill will be specified to be approximately 4 to 6 inches thick. This will be topped with a mud mat. Engineered fill is specified as a well drained granular backfill with a minimum friction angle of $\Phi = 35°$, and therefore providing the necessary friction resistance at the interface with the basemat. Potential sliding between engineered fill and natural clay is not likely due to penetration of granular soil particles into the natural soil during compaction. The possibility that a sliding surface goes through the fine grained soil, below its interface with the engineered fill, is analyzed in the following.

A pseudo-static analysis (equation 4.4-1), considering the largest horizontal innertia forces concurrent with the smallest basemat contact area (largest uplift) is performed to demonstrate that the minimum factor of safety for sliding stability, FS_{sl}^{min}, is larger than 1.1 when assuming that a sliding surface goes through clay subgrade. Only the cases involving subgrades with properties compatible with clay soil (namely profiles 270-500 and 270-200) are considered.

$$\mathrm{FS_{sl}^{min}} = \frac{\mathrm{r_{min}\,A\,c_u^{min}}}{\mathrm{F_I^{max}}} \geq 1.1 \qquad \text{Equation 4.4-1}$$

In equation 4.4-1, $r_{min} = 0.82$ is the minimum contact ratio at the base of the R/B complex, A ≈ 124,900 ft^2 is the surface area of the basemat, c_u^{min} is the minimum undrained shear strength in the clayey subgrade below basemat and F_I^{max} is the largest horizontal inertia force acting on the R/B complex during SSE.

The undrained shear strength for a clay soil compatible with the set of generalized layered subgrade profiles discussed in Reference 5 is estimated based on the minimum accepted values of the shear wave velocity (Vs) and using correlations available in the literature. Section 01.4.2 of Reference 5 states that the minimum Vs for the top 30 m (100 ft) must be greater than 1000 ft/s (305 m/s). The corresponding standard penetration number, corrected to 60% energy, N_{60}, is inferred from the minimum Vs using a correlation formula derived from Reference 29, Figure 12c. This formula, shown in equation 4.4-2, was selected here because it was obtained based on field data, gives a better error estimate compared to similar equations developed by other authors, and is specialized for clayey soils.

$$N_{60} = \exp\left\{\frac{\ln V_S - 4.679}{0.237}\right\} \qquad \text{Equation 4.4-2}$$

For Vs = 305 m/s, equation 4.4-2 gives $N_{60} \approx 81$ blows/ft. Equation (2.7) of Reference 30 provides a correlation between undrained shear strength (c_u) of insensitive clays and N_{60}, shown here in equation 4.4-3:

$$c_u = K\, N_{60} \qquad \text{Equation 4.4-3}$$

The constant K in equation 4.4-3 ranges between 0.073 ksf and 0.135 ksf (Reference 30). The minimum undrained shear strength in the clayey subgrade below basemat is obtained by using the lower bound of this range as c_u^{min} = 5.9 ksf.

The largest horizontal inertia force (F_I^{max}) acting on the R/B complex considering the design seismic acceleration for SSE (Reference 5) is about 513,000 kip. This force was obtained in the SSI analysis for the R/B complex with uncracked concrete section properties, placed on subgrade profile 270-200 and acted by the combination -X-Y-Z of the three components of the seismic input acceleration.

With the values conservatively estimated above, equation 4.4-1 results in a minimum factor of safety for sliding stability, for the case when the sliding surface is assumed to go through clay, $FS_{sl}^{min} \approx 1.18 > 1.1$.

In case of the T/B placed on clayey subgrade, the minimum force resisting to sliding through clay is $Ac_u^{min} \approx$ 403,000 kips, which is about 20% larger than the weight of the T/B. A verification such as that done for the R/B complex is therefore not necessary.

Based on the above considerations, a conservative value for the minimum friction angle of natural soil materials and engineered fill below the basemat for all profiles is selected to be $\Phi = 35^0$, corresponding to a minimum static friction coefficient $\mu_s = 0.7$ and a minimum kinetic friction coefficient $\mu_k = 0.5$.

<u>Effect of Groundwater</u>:

The friction coefficient between two surfaces in contact is in general affected by the presence of water, as the lubricating effect of water will usually reduce friction. However, the friction coefficient below the mud mat discussed here, representing friction between mass concrete and granular soil, is the result of shear failure in soil rather than of sliding between two surfaces. As discussed previously, this is because the cement penetrates in soil pores during mat placement and forces the failure surface to occur through soil rather than at the interface, and therefore the friction coefficient is an expression of the shear strength of soil. It has been verified experimentally that the results in terms of effective stresses and the shear strength of granular soils were not affected by the presence of water in the soil sample (e.g., Reference 21). Therefore, it is considered in this analysis that presence of water does not affect the friction coefficient between mud mat and subgrade.

Regarding the concrete-to-concrete and rock-to-concrete interfaces, all experimentally based values of the friction coefficient (References 16 and 18) discussed previously were obtained for both dry and wet interfaces.