RAI Volume 2, Chapter 2.1.1.7, Eleventh Set, Number 15:

> Provide (a) calculation of allowable bearing pressure for mat foundations of surface facility structures using appropriate strength parameters for the alluvium and limits on foundation settlement, and (b) justification for the settlement limits.
>
> Basis: DOE selected an allowable bearing pressure of 50 ksf (BSC, 2007ba, Section 6.2.3) for surface facility mat foundations based on BSC (2007bq, Figure B6-2). However, the DOE's information (BSC, 2007bq: Figures B6-7, B6-8, and B6-13) shows that the allowable bearing pressure based on limiting the foundation settlement decreases as the foundation width increases. This information (BSC, 2007bq: Figures B6-7, B6-8, and B6-13) indicates the allowable bearing pressure for the mat foundations could be much smaller than DOE's selected value of 50 ksf. Estimating the allowable bearing pressure for foundations on cohesionless soils based on limiting the foundation settlement is consistent with long-standing geotechnical engineering practice (e.g., Terzaghi et al., 1996, p.393–405).

1. RESPONSE

The approach for mat foundations at Yucca Mountain provides designs, which are acceptable with regards to both foundation pressure requirements and estimated settlements. The approach incorporates applicable requirements and defines necessary parameters. However, as part of this approach, no maximum allowable settlement limit for mat foundations is specified. Without such a limit, it is (computationally) not possible to perform a calculation for allowable bearing pressure (and prepare a resulting allowable bearing pressure diagram).

However, current foundation designs are appropriate and address the intent of the RAI:

- The design approach for mat foundations at Yucca Mountain uses a finite element model with soil springs to verify the acceptability of the mat design and meets the specified foundation pressure requirements based on the allowable bearing capacity of the soil units.
- The average foundation pressure for each surface facility is substantially less than the respective allowable bearing capacity and design requirements.
- The total settlement for each facility is less than an identified settlement goal based on empirical guidance.

The following response discusses these points in more detail. In addition, as requested in the June 3, 2009 clarification call, a diagram plotting foundation dimension versus an allowable bearing pressure is included for a rectangular foundation, based on previous soils analyses and an empirically based settlement goal. This figure is similar to Figures B6-7, B6-8, and B6-13 of *Supplemental Soils Report* (BSC 2008), which were prepared for strip and square footings.

As used in this response, two terms are defined: (1) allowable bearing capacity, which is the maximum pressure that can be imposed by the foundation onto the soil, providing an adequate factor of safety against the potential for shear failure of the soil, and (2) allowable bearing pressure, which is the maximum pressure that can be imposed by the foundation onto the soil, providing an adequate factor of safety against shear failure and against excessive settlement of the foundation. The important distinction between these two terms, and implicit in the bearing capacity equation (e.g., Terzaghi et al. 1996, Equation 33.7), is that the allowable bearing capacity includes no consideration for settlement. A third term is also introduced: maximum allowable settlement, which is the specified maximum total settlement for a foundation that will maintain building function and foundation integrity. The allowable bearing pressure is based on the definition of the maximum allowable settlement, as the allowable bearing pressure is limited so as not to induce settlements above this maximum allowable settlement value.

1.1 APPROACH FOR MAT FOUNDATION DESIGN

The design approach for large mat foundations for the surface facilities does not utilize a prescribed settlement limit as a design criterion. Rather, foundation pressure limits are specified based on the allowable bearing capacity for the soil units and engineering judgment (BSC 2008, Table 2-2). Within these limits, an initial design is prepared that meets facility requirements for static and dynamic loads. Then, analyses examine the deformation of the designed foundation mat using a finite element model to examine stresses and deformations in the mat to ensure that the design is acceptable based on design codes and facility requirements. Finally, using this design as a basis, analyses are performed to examine the expected total and differential settlements of the structure to identify any potential area of concern.

As to the specified foundation pressure limits for mat foundations, *Project Design Criteria Document* (BSC 2009, Section 4.2.11.6.7) indicates that foundation design parameters of Table 2-2 from *Supplemental Soils Report* (BSC 2008) shall be included in the design. Table 2-2 of *Supplemental Soils Report* (BSC 2008) indicates that a foundation pressure limit for mat foundations of 50 ksf is to be used in the case of extreme (seismic) loads and a limit of 10 ksf for normal loads. These maximum foundation pressure limits are utilized as a basis for subsequent design.

As described in *CRCF Foundation Design* (BSC 2007a), a finite element model of the Canister Receipt and Closure Facility foundation mat is developed and coupled to the lumped mass, “beam-stick” (or “multiple stick”) model, which is constructed for the Canister Receipt and Closure Facility seismic analysis. The result is a finite element model of the foundation mat with the stiffening effects of the walls included. The computer code, SAP2000, is used for these analyses.

Nonlinear, compression-only springs are used to model the soil underlying the foundation mat. Dead, live, and seismic loads are applied to the model, and loading combinations are developed that maximize the soil pressures on each corner of the structure. Static and seismic load combinations were developed per Appendix A of *Seismic Analysis and Design Approach Document* (BSC 2007b). Since a nonlinear spring element is utilized to model the soil stiffness, a nonlinear analysis is required for each loading combination (i.e., the principle of superposition does not apply). In each analysis case, SAP2000 obtains a solution and then verifies that all spring elements are in compression. If tension exists in any spring element, SAP2000 removes these springs and resolves the problem. SAP2000 continues this iterative process until the solution converges and no tension exists in any spring elements.

Having completed the nonlinear analysis, moment and shear contour plots are then generated using SAP2000. These plots are used in designing the shear and flexural reinforcing in the foundation mat. In designing the flexural reinforcing, a standard rebar pattern is selected, and the corresponding moment capacity resulting from that reinforcing is computed. The contour plots are then utilized to identify areas that may require additional reinforcing above the standard reinforcement pattern. In evaluating the shear reinforcing requirements in the foundation mat, the shear capacity of the concrete (without any reinforcing considerations) is computed, and the shear contour plots are utilized to determine areas of the foundation mat requiring transverse shear reinforcing. Transverse shear reinforcing is then designed to provide the additional capacity required above the capacity provided by the concrete. In addition, energy balance methods (discussed in ASCE/SEI 43-05) are used to compute the maximum predicted sliding displacement.

After design analyses have been completed in accordance with applicable design codes, the resulting foundation pressures are examined to ensure that the foundation pressure limit is not exceeded and that the structure is stable against overturning. The average total and differential settlements are also estimated for the facility. Potential foundation displacements (if judged tolerable) are then included in requirements for the flexibility of any commodities or utilities entering the structure or in the clearance to any adjacent structures.

1.2 ALLOWABLE BEARING CAPACITY AND FOUNDATION PRESSURES

The value of 50 ksf cited in *Seismic Analysis and Design Approach Document* (BSC 2007b, Section 6.2.3) and shown in Figure B6-2 of *Supplemental Soils Report* (BSC 2008) provides guidance based on the bearing capacity of mat foundations in the geologic repository operations area. The statement on allowable bearing capacity in context is (BSC 2007b, p. 16):

> Due to the relatively dense granular nature of the alluvium at the site, the *bearing capacity*, particularly for the large foundation mats, is 50 ksf or more ... This bearing capacity exceeds the anticipated foundation pressure imposed from the structures. [Emphasis added]

To demonstrate that the allowable bearing capacity for large foundation mats is in excess of 50 ksf, an allowable bearing capacity evaluation was performed for each important to safety (ITS) surface facility. For comparison, the average foundation pressure for these facilities is also calculated.

The allowable bearing capacity was evaluated for each facility using the dimensions of the surface facilities, typical soil properties identified in *Supplemental Soils Report* (BSC 2008, Appendix B), and the bearing capacity equations provided by *Foundation Analysis and Design* (Bowles 1996). The values are listed in Table 1. Diagrammatically, a plot of allowable bearing capacity for a rectangular foundation (with a plan dimension ratio of 1:2) is also provided in Figure 1. This figure is similar to Figure B6-2 of *Supplemental Soils Report* (BSC 2008).

From an examination of results in Table 1, it is evident that the allowable bearing capacity for each facility is substantially in excess of the 50 ksf value, as stated in *Seismic Analysis and Design Approach Document* (BSC 2007b), and is generally larger than 90 ksf. It is also shown that the average foundation pressure (i.e., the total weight of the structure divided by the foundation area) for each facility is substantially less than this allowable bearing capacity, demonstrating that the foundation design is acceptable with regard to the shear failure of the soil. Further, the average foundation pressure for each facility meets the requirement of *Supplemental Soils Report* (BSC 2008) for a foundation pressure limit of 10 ksf for normal loads on a mat foundation.

As a clarification, it is noted that the caption of Figure B6-2 mentions "allowable bearing *pressure*," but the Y-axis of the figure and preceding analytical representation in *Supplemental Soils Report* (BSC 2008) indicates that the lines plotted are for "allowable bearing *capacity*." The figure caption will be clarified in a future revision of the report, as appropriate.

1.3 MAXIMUM ALLOWABLE SETTLEMENT AND ESTIMATED FACILITY SETTLEMENTS

When specified as a design requirement, the maximum allowable settlement for a mat foundation is typically based on various design considerations, including facility use and access requirements. From a solely geotechnical viewpoint, the most important concern is the differential settlement of a foundation. Differential settlement can induce stresses in the foundation mat, leading to cracking and, if large enough, to foundation failure. As differential settlement can be empirically related to the total settlement of the foundation, settlement requirements can be specified in terms of either differential or total settlement. For this response, the maximum allowable settlement is defined in terms of total settlement.

To identify an acceptable amount of foundation settlement, guidance on allowable settlements for a mat foundation on sand is obtained from the literature. As indicated in *Foundation Analysis and Design* (Bowles 1996, Table 5-7), the range of differential settlement for the observed satisfactory structural performance of a mat (or "raft") foundation on sand was found to be 50 to 75 mm (2 to 3 in.), based on two field studies. The values recommended for design ranged from 35 to 65 mm (1.4 to 2.5 in.). Using an approximation that the observed differential settlement is three-fourths the total settlement (Bowles 1996, p. 339), the recommended differential values can be translated into a range of total settlement of 47 to 87 mm (1.8 to 3.4 in.) recommended for a raft design. Terzaghi et al. (1996, Section 51.2.1) indicates that a raft foundation can sustain larger settlements than foundations on footings and that rafts can sustain twice the values assigned by recommended design equations for footings. Terzaghi et al. (1996) also concludes that a total settlement of a raft foundation on sand of the magnitude of 50 mm (2 in.) is ordinarily of no concern. Further, the European Committee for Standardization has identified 50 mm (2 in.) of differential settlement as a limiting value for serviceability for raft foundations (Das 2007, p. 266). Based on the foregoing, a maximum allowable (total) settlement of 2 in. can be identified as an appropriate goal for mat foundations within the geologic repository operations area.

Settlement analyses have been performed for the ITS surface facilities in the geologic repository operations area. These analyses estimated a total settlement based on the addition of instantaneous and long-term settlements. The instantaneous settlements are estimated using an equivalent spring coefficient method, using shape and rigidity factors from *Foundations and Earth Structures* (USN 1986, p. 7.1-213), and the long-term settlement is based on the standard penetration method described by Terzaghi et al. (1996, Section 50.2.5). These analyses consider the depth to bedrock as a parameter, since the thickness of alluvium below all structures is relatively shallow with respect to the mat foundation dimensions (as evidenced by the maximum alluvium thickness in most cases being less than the foundation dimension *B*). The estimated settlement results are listed in Table 1.

In comparing the estimated total settlements of the facilities to a maximum allowable settlement of 2 in., the total settlement for each facility in Table 1 is less than 2 in., and in most cases, is about 1 in. A comparison can also be made for differential settlements. Converting the maximum allowable settlement to differential settlement, a comparable differential settlement value of 1.5 in. can be identified. As shown in Table 1, the largest estimated differential settlement for any facility is 0.8 in., which is about half the 1.5 in. value. These results demonstrate that the foundation designs for the surface facilities are acceptable with regard to the identified settlement goal.

1.4 ALLOWABLE BEARING PRESSURE

Using a maximum allowable settlement of 2 in., the allowable bearing pressure for larger mat foundations can be evaluated as a function of foundation dimensions, employing the same parameters and approach developed in *Supplemental Soils Report* (BSC 2008, Appendix B). The allowable bearing pressure evaluations are performed employing the methods shown in *Foundation Analysis and Design* (Bowles 1996) and *Soil Mechanics in Engineering Practice* (Terzaghi et al. 1996) for a rectangular foundation. For these analyses, the larger foundation dimension (*L*) is taken as twice the smaller dimension (*B*) as representative of the foundation dimension ratio (*L/B*) of the ITS surface facilities (see Table 1). This is a conservative approach, as a rectangular foundation will have a smaller allowable bearing pressure than a square foundation for the same dimension *B*. Figure 2 provides the allowable bearing pressure for a rectangular foundation with a maximum allowable settlement of 2 in. without consideration for the shallow depth to bedrock at the site.

As shown in Figure 2, the allowable bearing pressure decreases sharply from about 23 ksf for *B* greater than 25 ft, and becomes asymptotic to approximately 9.9 ksf at $B = 300$ ft. As a generalization, for foundations for *B* greater than 150 ft, the 9.9 ksf value can be used as a lower bound for the maximum allowable bearing pressure for ITS facilities mat foundations. The average foundation pressures for ITS structures all readily meet this criterion. From an examination of Table 1, the average foundation pressure for all ITS surface facilities is less than half of this 9.9 ksf value, demonstrating acceptable foundation design pressures.

This comparison demonstrates that the foundation designs for ITS surface facilities are acceptable with regard to the allowable bearing pressure for the local soils with a maximum allowable settlement of 2 in.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

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Table 1. Foundation Parameters, Average Foundation Pressure, Allowable Bearing Capacity, and Estimated Settlement for Surface Facilities

Building	Effective [Maximum] Foundation Width, B (ft)[a]	Effective [Maximum] Foundation Length, L (ft)[a]	Foundation L/B Ratio	Foundation Mat (Slab) Thickness (ft)	Foundation Embedment Depth (ft) a	Maximum Depth to Bedrock (ft)[b]	Average Foundation Pressure (ksf)	Allowable Bearing Capacity (ksf)	Estimated Total Settlement, δ (in.)	Estimated Differential Settlement (in.)
CRCF1	262 [421]	331 [262]	1.3 [1.6]	6	5	116	3.33	243	1.0	0.6
CRCF2	262 [421]	331 [262]	1.3 [1.6]	6	5	179	3.33	243	1.1	0.6
CRCF3	262 [421]	331 [262]	1.3 [1.6]	6	5	186	3.33	243	1.2	0.7
IHF Cask Process Area	170	196.5	1.2	6	5	81	1.70	158	0.6	0.6
IHF Loadout Area	75	141.5	1.9	6	5	81	3.05	89	0.6	0.6
WHF (Pool)	114	116	1.0	8	59	48	3.22	314	–[c]	–[c]
WHF (Building)	214	270	1.3	6	5	92	4.67	201	1.0	0.8 (0.4)[d]
RF	242 [284]	200 [242]	1.2 [1.2]	7	6	134	3.45	189	1.0	0.6
EDGF	98	174	1.8	4	3	95	1.68	105	0.5	0.3

NOTE:

[a] Effective foundation dimensions were used in bearing capacity evaluations and exclude alcove foundations and secondary mat extensions. Maximum dimensions, shown in brackets where different from effective dimensions, were used in settlement estimates. Embedment depth is taken in general as the mat thickness minus 1 ft; however, for the WHF pool, embedment depth is taken as the depth below grade, rounded down to the nearest foot.

[b] The maximum depth to bedrock (or the maximum alluvium thickness) is determined from the depth to rock of the nearest borings to each structure. Depth is measured from foundation base elevation to the deepest elevation of rock.

[c] The weight of removed soil for the WHF pool exceeds foundation load of pool. Due to the preconsolidation loading of the soil, little additional settlement due to the pool foundation loading is expected for the weight of the pool alone.

[d] The total and differential settlement values for WHF building (shown without parenthesis) do not include the presence of pool structure; the settlement estimate uses the average weight of the structure, including pool walls, base, and water weight distributed equally within the outer building footprint. The value within parenthesis for differential settlement considers the settlement of the interior pool as negligible and the potential differential settlement is limited to that which occurs between the outer building (mat) edge and the outer pool edge.

B = shorter dimension of foundation in plan; CRCF = Canister Receipt and Closure Facility; EDGF = Emergency Diesel Generator Facility; IHF = Initial Handling Facility; *L* = longer dimension of foundation in plan; RF = Receipt Facility; WHF = Wet Handling Facility.

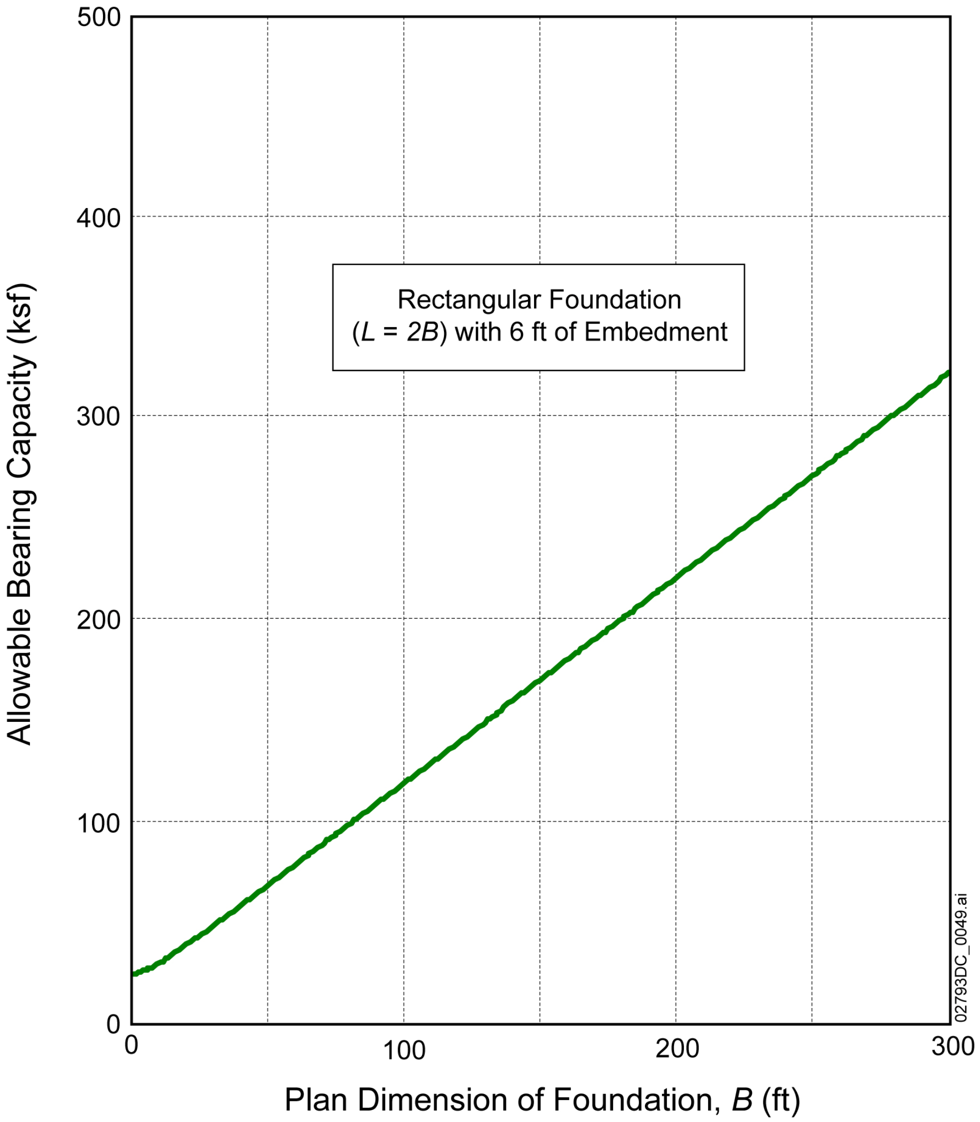

Figure 1. Allowable Bearing Capacity Versus Dimension *B* for a Rectangular Foundation (*L* = *2B*)

NOTE: The allowable bearing capacity evaluation is based on equations developed by Hansen (1970), as presented in Bowles (1996). Parameter values for the evaluation are from *Supplemental Soils Report* (BSC 2008).

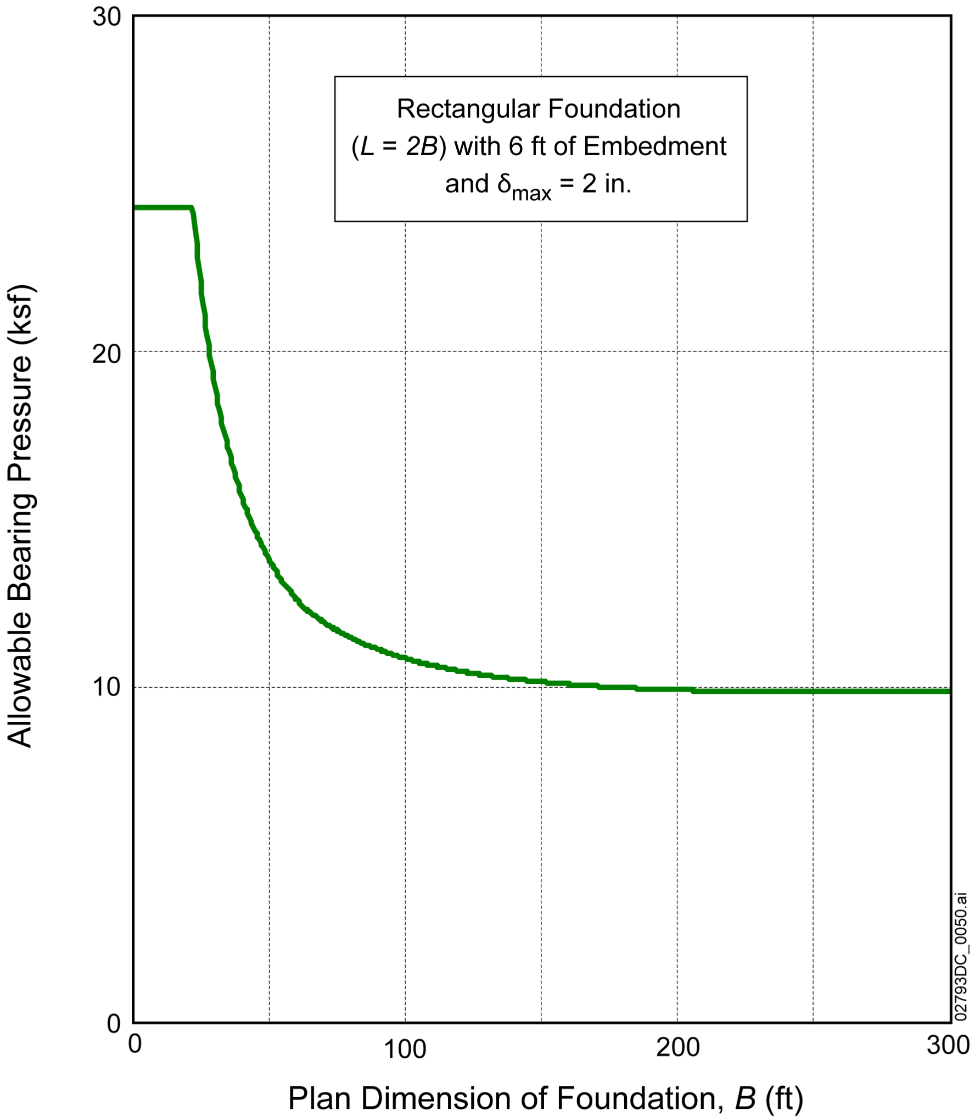

Figure 2. Allowable Bearing Pressure Versus Dimension *B* for a Rectangular Foundation (L = $2B$) with a 2-in. Maximum Allowable Settlement Criterion

NOTE:

1. Settlement was evaluated using the method developed by Schmertmann (1970) and Schmertmann et al. (1978), as presented in *Soil Mechanics in Engineering Practice* (Terzaghi et al. 1996). Bearing capacity was evaluated using the method developed by Hansen (1970). Parameter values are from *Supplemental Soils Report* (BSC 2008).
2. Analyses assume that bedrock is sufficiently deep not to affect settlement or allowable bearing capacity.
3. Dimension *B* is the smaller foundation dimension in plan.