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February 22, 2024

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Georgia Department of Natural Resources
Environmental Protection Division
Watershed Protection Branch
Safe Dams Program
2 Martin Luther King, Jr. Drive SE
Suite 1052 East Tower
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Subject: Independent Review of Seismic Stability Analyses Performed by Geosyntec, Lake Petit Dam, Pickens County, Georgia (Schnabel Reference Number 23170093.000)

Dear Mr. Griffin:

SCHNABEL ENGINEERING, LLC (Schnabel) completed the authorized review of the seismic stability analyses performed by Geosyntec Consultants (Geosyntec) for the Lake Petit Dam in Pickens County, Georgia. The details of Schnabel's review, including a synopsis of the work performed Geosyntec and Schnabel's interpretation of the analyses and results, are summarized herein. Schnabel's review was performed for the Georgia Safe Dams Program (SDP) in general accordance with Schnabel's proposal dated September 15, 2023, and authorized via a contract from the State of Georgia dated October 27, 2023.

1.0 BACKGROUND AND SCOPE OF SERVICES

Lake Petit Dam is located within the Big Canoe development in Pickens County, Georgia. The Big Canoe Property Owners Association owns and operates the dam. The 126-foot-tall earthen embankment dam has a maximum storage capacity of approximately 5,635 acre-feet at the crest of dam elevation of 1648 feet (NAVD88). The subject dam is currently classified by the SDP as a Category I or 'high-hazard' structure. Category I structures are regulated by the SDP and must comply with the criteria defined by the Rules and Regulations of the State of Georgia, to include the embankment meeting minimum slope stability factors of safety for specific loading conditions.

In April 2023, Geosyntec submitted a reported entitled "Stability Analysis of Lake Petit Dam" (Geosyntec Report) to the SDP for review. The Geosyntec Report presents data, engineering calculations, methodology, stability models/evaluations, results, and conclusions for various applicable and required slope stability loading conditions, including seismic loading, for Lake Petit Dam. The results presented in the Geosyntec Report indicate that the existing embankment dam complies with the minimum factor of safety for the modeled or simulated seismic loading scenario. The SDP requested that an independent review of the seismic analysis presented in the Geosyntec Report, to be performed in support of the SDP's review of the entire Geosyntec Report.

The scope of services performed by Schnabel for the independent review comprise:

- Review of provided data, model inputs, methodology, and model outputs relevant to the seismic analyses presented in the Geosyntec Report.
- Evaluation of the results of the seismic analysis presented in the Geosyntec Report.
- Preparation of a summary letter report presenting Schnabel's opinion of the appropriateness of the seismic analysis as prepared by Geosyntec Consultants, including comments regarding the seismic analysis for consideration by the SDP.
- Coordination with the Engineer and SDP, as needed, to discuss the summary report prepared by Schnabel as part of this engagement.

2.0 SUMMARY OF CONCLUSIONS

The Geosyntec Report presents a seismic slope stability assessment of the subject dam using pseudostatic limit equilibrium slope stability analysis methodologies with a horizontal seismic coefficient (k_h) of 0.054, which was selected based on permanent displacement potential. Determination of k_h relied on the 2018 USGS National Seismic Hazard Model (NSHM) to assess the seismic hazard of the site, site-specific shear wave velocity (V_s) measurements conducted in boreholes to evaluate the fundamental period of the dam, and an assumed allowable permanent seismic slope displacement of 60 cm (2 feet). The pseudostatic factor of safety (FS) calculated using these parameters was reported by Geosyntec to be 1.5 (downstream) and 2.4 (upstream), which meet the minimum requirements established by the SDP. Geosyntec also evaluated the sensitivity of the seismic stability analyses by considering a range of k_h values.

Based upon the experience of the undersigned representatives of Schnabel, the approach adopted by Geosyntec is suitable for the project and the conclusion complies with the minimum factor of safety for a seismic loading condition defined by the SDP. A brief background on seismic slope stability analyses and specific review comments are provided in the sections below.

3.0 DESIGN CRITERIA

The SDP seismic loading conditions are defined in the Rules and Regulations of the State of Georgia, "Rule 391-3-8-.09, Standards for the Design and Evaluation of Dams,", which specify (bolded portions relate specifically to seismic stability):

"…(3) Design and Evaluation of Dams under paragraph (1) and (2) above shall, as a minimum, consider the following basic principles:

> *(a) All dams must be stable under all conditions of construction and/or operation of the impoundment. Details of stability evaluation shall be submitted to the Director for approval. Analyses using the methods, guidelines and procedures of the agencies listed in paragraph (1) yielding the following Minimum Safety Factors can be considered as acceptable stability:*
>
> > *1. Earthen Embankments*

(i) *End of Construction: 1.3*

(ii) *Steady State Seepage: 1.5*

(iii) ***Steady State Seepage with Seismic Loading: 1.1***

(iv) *Rapid Drawdown (Upstream): 1.3*

(v) *Submerged Toe with Rapid Drawdown: 1.3*

2. *Concrete Structures (cohesion included)*

(i) *Normal Reservoir: 3.0*

(ii) *Normal Reservoir with Seismic Loading: 1.0*

(iii) *Design Flood: 2.0*

(b) *Details of the engineering evaluation of material properties in the dam or appurtenant structures shall be submitted to the Director for review and approval. Conservative selections for soil strength values shall be used for analyses or evaluations. Details of any foundation investigation and laboratory testing supporting assumed design or evaluation parameters shall be included for review.*

(c) ***All dams and appurtenant structures shall be capable of withstanding seismic accelerations defined in the most current "Map for Peak Acceleration with a 2% exceedance in 50 years" for the contiguous United States published by the United States Geological Survey (NEHRP maps). The minimum seismic acceleration shall be .050 g. The seismic accelerations may be reduced or seismic evaluation eliminated if the applicant's engineer can successfully demonstrate to the Director by engineering analyses or judgment that smaller seismic accelerations are appropriate or no seismic evaluation is needed****…."*

4.0 BACKGROUND ON SEISMIC SLOPE STABILITY ASSESSMENT

Seismic slope stability assessments can be performed using multiple methods, some of which are summarized in this section. A common method used in slope stability assessment is the so-called pseudostatic stability analyses comprising a traditional limit equilibrium slope stability analysis with addition of a horizontal seismic coefficient (k_h) to represent the earthquake or seismic induced load on the embankment or structure. The horizontal seismic coefficient is a numerical simplification of dynamic and variable earthquake ground shaking. Importantly, there is no industry standard approach to select an appropriate k_h value; however, there are some typical conventions used in practice, which are discussed below.

The results of pseudostatic seismic slope stability analyses are typically assessed against a target factor of safety (FS). However, this is an incomplete seismic stability assessment when considered in isolation because pseudostatic analyses do not necessarily correlate with seismic performance requirements for specific structures. That is, a low FS could imply the dam would suffer large displacement, which may result in catastrophic failure or simply a tolerable loss of freeboard. This disconnect between FS and performance is largely due to the simplification of earthquake loading and seismic response of the dam into the single parameter k_h.

Incorporation of permanent seismically induced displacement to supplement pseudostatic stability analyses has been studied since the 1970's (e.g., Makdisi and Seed, 1978), and multiple approaches have been developed to consider permanent seismically induced displacements with pseudostatic FS-based criteria (e.g., Hynes-Franklin and Griffin, 1984). It is common for k_h to be specified as a fraction of the peak ground acceleration (PGA) at the design hazard level to account for seismic displacement potential. For example, Hynes-Franklin and Griffin (1985) recommended k_h values of 0.5 X PGA and FS of 1.0 to limit the potential seismic displacement to 1 m (3.3 ft).

Figure 1 summarizes some historical methods for performing pseudostatic analyses. For clarity, the reference acceleration (a_{ref}) shown in Figure 1 is either the PGA at the foundation level (PHA_{rock}) or at the crest or top of slope area (PHA_{soil}).

(1) Reference	(2) Reference acceleration, a_{ref}	(3) Acceleration multiplier, a/a_{ref}	(4) Strength reduction factor	(5) Minimum factor of safety	(6) Tolerable displacement
Makdisi and Seed (1978)	0.2 g ($M \approx 6\frac{1}{2}$)	0.5	0.8	1.15	Approx. 1 m
Makdisi and Seed (1978)	0.75 g ($M \approx 8\frac{1}{4}$)	0.2	0.8	1.15	Approx. 1 m
Hynes-Griffin and Franklin (1984)	PHA_{rock}	0.5	0.8	1.0	1 m
Bray et al. (1998)	PHA_{rock}	0.75	Recommend using conservative (e.g., residual) strengths	1.0	0.30 m for landfill covers; 0.15 m for landfill base sliding
Kavazanjian et al. (1997)	PHA_{soil}	0.17 if response analysis is performed	0.8[a]	1.0	1 m
Kavazanjian et al. (1997)	PHA_{soil}	0.5 if response analysis is not performed	0.8[a]	1.0	1 m

[a]For fully saturated or sensitive clays.

Figure 1: Suggested Methods for Performing Pseudostatic Screening Analyses (Table 10.1, Duncan and Wright, 2005)

A simplified seismically induced displacement model (e.g., Bray and Travasarou, 2007; Bray and Macedo, 2019) can also be used independently as a screening tool to assess dam crest displacement potential. In fact, seismically induced displacement analyses are sometimes specified to entirely supersede the pseudostatic analysis. That is, a low pseudostatic FS may be acceptable provided the potential seismic displacements meet the design performance target for the specific dam.

There are multiple seismic displacement models available in practice. While each model is different, they generally consider seismological and geotechnical site conditions with the seismic "strength" of the slope represented by the yield seismic coefficient (k_y). k_y is the k_h at which the pseudostatic FS is equal to 1. The yield seismic coefficient is not linked to the seismic hazard level or design PGA like k_h when performing a pseudostatic analysis as described above (Figure 1). Simplified seismic displacement models are generalized tools and some level of conservatism is recommended when they are used deterministically. For example, the Bray methods referenced above are often used as a screening-level assessment based on the 84th percentile displacement level (mean plus one standard deviation), instead of the 50th percentile (i.e., mean).

A more thorough estimate of seismic displacement is possible through the use of dynamic numerical analyses (e.g., finite element analyses). Dynamic numerical analyses are typically performed in situations where the results of the simplified analyses are marginal or inconclusive. Dynamic numerical analyses comprise propagating multiple earthquake ground motions through a numerical model of the dam. These analyses require detailed, site-specific seismic hazard information, geophysical measurements of both the dam and foundation, and specific data to characterize the geotechnical and dynamic properties of the dam materials (often including cyclic laboratory testing). The increased time and cost to perform dynamic numerical analyses often precludes their use.

All methods discussed in this section have limitations when considering seismic liquefaction and cyclic softening, for example:

- Pseudostatic analyses and simplified slope displacement analyses assume that the shear strength of the soil is constant during earthquake shaking. The impact of shear strength reduction because of seismic phenomena like liquefaction and cyclic softening cannot be captured in these analyses. Dynamic numerical analyses have the capability to simulate liquefaction and cyclic softening, but these require advanced models that need a higher level of expertise to perform and require even more detailed geotechnical data with greater time and cost than is needed for other numerical analyses. As a result, liquefaction and cyclic softening numerical models are not commonly used in current practice. Thus, the potential for strength loss and its impact on seismic performance of the dam is almost always considered separately, except in the rare cases where advanced numerical models are used.
- Both simplified and numerical seismic displacement analyses discussed above refer to horizontal shear-induced permanent displacement. Densification due to ground shaking and post-liquefaction reconsolidation settlement are potential vertical displacement mechanisms that can impact a dam, but neither is captured in the simplified or typical numerical seismic displacement analyses. Advanced dynamic and liquefaction constitutive models have the capability to assess seismic densification and post-liquefaction reconsolidation, but these models are not fully developed and require significant expertise and experience to use. Therefore, densification due to ground shaking and post-liquefaction reconsolidation settlement are commonly considered separately from the displacement analyses discussed above.

5.0 REVIEW COMMENTS AND DISCUSSION

Comments on the Geosyntec analysis approach, parameters, and results are discussed below.

5.1 Approach for Seismic Stability Assessment

5.1.1 Geosyntec Approach

Geosyntec performed pseudostatic limit equilibrium stability analyses with steady-state seepage conditions for their assessment of seismic stability of the dam.

5.1.2 Discussion

The SDP requirement specify a minimum factor of safety, the design seismic hazard level, the method for estimating design ground motions, and the minimum PGA. In our opinion, a pseudostatic analysis is implied by the SDP requirement because of the specification of a minimum factor of safety, which is typically associated with limit equilibrium slope stability analyses, and because PGA is often specified in conjunction with or as a proxy for k_h. In our experience, Geosyntec's approach is typical in practice and is appropriate for demonstrating compliance based on our interpretation of the SDP requirements.

5.2 Seismic Hazard Information

5.2.1 Geosyntec Approach

Geosyntec used the 2018 USGS National Seismic Hazard Model available online through the USGS website (e.g., https://earthquake.usgs.gov/nshmp/) to estimate the seismic hazard at the 2,475-year return period hazard level. The results of this assessment comprise a PGA and uniform hazard spectrum presented in Attachment 1 of Geosyntec's report.

Geosyntec used site class D to obtain seismic hazard information representative of the base of embankment. Site class D represents stiff soil conditions with $V_{s,30}$ (i.e., travel-time-averaged shar wave velocity over the upper 30 m/100 ft) of 185-365 m/s (600-1200 ft/s).

5.2.2 Discussion

The foundation of the dam is stiffer (faster $V_{s,30}$) than site class D used by Geosyntec, so use of site class D is conservative for assessing the seismic hazard at the base of the embankment.

The USGS is in the process of releasing their updated 2023 NSHM, which can be viewed online in beta form. The ground motion intensity for the 2475-year return period hazard level at the site is 10-25% greater in the beta 2023 NSHM than in the current 2018 NSHM used by Geosyntec. However, Geosyntec's sensitivity analyses discussed below covers a range of values that exceed the likely potential differences between beta 2023 and 2018 NSHM so it is possible to evaluate the potential differences in the stability assessment arising from the model update. In addition, Geosyntec made other conservative decisions in their approach that would potentially offset the impact of an increase in ground motion intensity in the next NSHM update. These items are discussed subsequently.

Geosyntec's approach uses the current version of the USGS NSHM. The SDP could consider having the seismic stability assessment updated once the 2023 USGS NSHM is released, but based on our judgement, this is unlikely to change Geosyntec's overall conclusion.

5.3 Selection of k_h and Performance of Pseudostatic Stability Analyses

5.3.1 Geosyntec Approach

Geosyntec used a k_h of 0.054 for their design analyses and considered a range of k_h from 0.038 to 0.2 for sensitivity analyses.

The horizontal seismic coefficient and the subsequent stability analysis were performed following the approach proposed by Bray and Travasarou (2009), which comprises the following:

- First, k_y is calculated for a potential seismic displacement using the model of Bray and Travasarou (2007). For clarity, note that Bray and Travasarou (2009) provides an approach for considering displacement in the pseudostatic analysis and Bray and Travasarou (2007) presents a probabilistic simplified slope displacement model that is used in the approach presented in Bray and Travasarou (2009). Also note that Bray and Travasarou (2007 and 2009) and Geosyntec use the notation of k_s instead of k_y when referring to the seismic coefficient calculated based on displacement potential.

- Second, pseudostatic stability analyses are performed with k_s.

- Last, the potential slope displacement is assumed to be smaller than the assessment displacement if the FS is above 1.0, and vice versa if the FS is below 1.0.

Input parameters used by Geosyntec to calculate k_s comprised the following:

- Allowable permanent seismic displacement of 60 cm (2 feet).

- Initial fundamental period (Ts) of 0.285 s, which was estimated based on V_s data collected through the dam centerline using the equations provided by Bray and Travasarou (2007). V_s used for estimating Ts was measured by Geosyntec and presented in their 1998 report, excerpts of which are included in the 2023 stability analysis report.

- Moment magnitude (Mw) of 7.0, which was assumed considering the seismic sources contributing to the seismic hazard for the site.

- Spectral acceleration at 1.5 times Ts (Sa(1.5Ts)) of 0.31 g, which was interpolated from the uniform hazard spectra reported by Geosyntec. Note that Bray and Travasarou (2007) consider the base of the potential sliding mass as the reference level for Sa(1.5Ts), that is, the level near the base of the dam or top of foundation.

- Epsilon (ε) of 1.32 to represent the 90^{th} percentile displacement level.

5.3.2 Discussion

Selection of a seismic-hazard-consistent k_h is not straightforward because the relationship between PGA and k_h varies depending on the analysis method and the desired seismic performance, as discussed in section 4.0 of this letter report. To overcome this, Geosyntec selected a seismic-hazard consistent k_h following the approach of Bray and Travasarou (2009) for an assumed allowable seismic displacement of 60 cm (2 feet). The SDP should verify that 2 feet of potential seismic displacement is tolerable for the dam; however, note that the sensitivity analyses performed by Geosyntec indicates smaller potential displacement of less than 10 cm (4 inches), as discussed in section 5.6 of this letter report.

In our opinion, Bray and Travasarou (2009) is often used in practice, but as mentioned above, there is no industry consensus and older methods, like Hynes-Griffin and Franklin (1984), are also used in practice. We support the use of Bray and Travasorou (2007 and 2009) because they were developed by coupling the seismic response and seismic displacement analyses, which is an improvement over older methods. Furthermore, Bray and Travasarou (2007) considered a larger ground motion database in development of their model than was available in development of older methods, and was built probabilistically so the user can assess the relative uncertainty of the estimated displacement, which cannot be done with older methods.

Geosyntec used site-specific V_s measurements to estimate Ts. Direct site measurement of V_s is the preferred approach as opposed to correlation of V_s with standard penetration test or cone penetration test data. These correlations generally do not perform well and have a high uncertainty. Based on our experience with Bray and Travasarou (2007 and 2009), seismic displacement and k_s are not highly sensitive to Ts. The SDP could consider conducting additional V_s measurements to assess the potential variability of Ts or perform further sensitivity analyses incorporating Ts, but in our opinion, this is unlikely to change Geosyntec's overall conclusion.

Geosyntec used Mw of 7.0, which is slightly larger than the mean Mw contributing to the hazard at 1.5Ts. For discussion, Figure 2 shows the deaggregation plot for 2475-year return period, 0.4 s vibration period, site class C/D obtained from the online tool for the USGS 2023 NSHM (beta version). Figure 2 is similar to the equivalent plot for the 2018 NSHM, which has not been included for brevity. Figure 2 indicates that the hazard is influenced by regional gridded seismicity and the further distant New Madrid Seismic Zone. Although a few Mw and distance (R_{rup}) bins for the New Madrid Seismic Zone have the largest individual contribution to the hazard, the cumulative contribution of the local gridded seismicity is significantly greater than the New Madrid Seismic Zone. In this context, Mw of 7.0 is slightly larger than the mean of the contributing Mw for the regional gridded seismicity and less than the contributing Mw of the New Madrid Seismic Zone. In our opinion, Mw 7.0 is a reasonable choice for the 2475-year return period hazard because it is about equal to the overall mean Mw for the hazard. The SDP could consider further sensitivity analyses to assess the effect of a greater Mw in line with earthquakes generated in the New Madrid Seismic Zone, remembering that these earthquakes produce ground motions with smaller contribution to the hazard than the contribution of those produced by regional gridded seismicity.

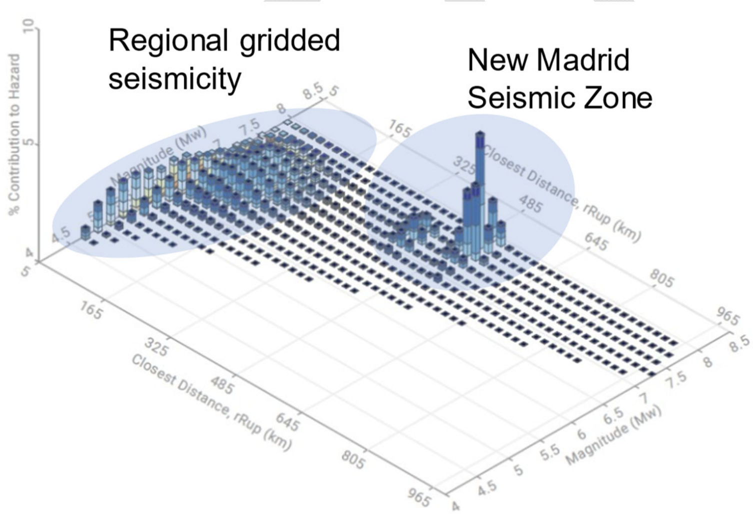

Figure 2: Deaggregation Plot for 2475-year Return Period, T = 0.4 s, Site Class C/D (USGS 2023 NSHM, beta version)

Spectral acceleration at 1.5 times Ts (Sa(1.5Ts)) is a model parameter that is estimated based on the seismic hazard information, which was conservatively assessed using site class D with the 2018 USGS NSHM as discussed in section 5.2 of this letter report.

Geosyntec calculated k_s for the 90th percentile displacement estimated with the Bray and Travasarou (2007) model. This is a conservative approach in comparison with using the 50th percentile (i.e., mean). Furthermore, Geosyntec appears to have ignored the standard deviation (σ) in calculation of ε. Note that in the literature, ε typically represents the number of standard deviations from the mean, but in Bray and Travasarou (2007 and 2009) ε is given as the product of ε and σ. Ignoring σ in this case has a conservative effect on the analysis and the value of 1.32 represents the 98th percentile of the Bray and Travasarou (2007) model.

5.4 Shear Strength and Geotechnical Parameters

5.4.1 Geosyntec Approach

Geosyntec performed pseudostatic stability analyses using undrained shear strength parameters for both the dam shell and core.

5.4.2 Discussion

A cursory assessment of geotechnical characterization and seepage modeling was performed for this review. In our opinion, the selected geotechnical and seepage parameters are within typical values for the types of soil and rock discussed by Geosyntec. We also agree that undrained shear strength parameters are appropriate for pseudostatic stability analyses.

Figure 1 indicates a strength reduction factor be used for the listed historical pseudostatic methods. The basis for this recommendation is the observation by Makdisi and Seed that cyclic laboratory tests on clay generated shear strains in a generally controlled manner and the tests could tolerate many cycles of loading (more than 100) if the cyclic stress was less than about 80 % of the yield stress. Makdisi and Seed (1978) recommended the use of the reduced “dynamic yield strength” as a method of notionally preventing large uncontrolled displacements, which were not captured in their modeling.

Neither Bray and Travasarou (2007) or (2009) mention a specific strength reduction factor, but in our opinion, it is typical practice to select conservative undrained shear strength parameters. Figure 3 shows that Geosyntec selected a lower bound undrained shear strength based on their laboratory data. For reference, the dashed line shown in Figure 3 was added by Schnabel at 1.25 times the Geosyntec strength (i.e., the Geosytnec strength is 80% of the dashed blue line). Visually, the dashed blue line appears to be a reasonable fit to the laboratory data, which suggests that Geosyntec’s undrained shear strength characterization is generally consistent with the dynamic yield strength recommended by Makdisi and Seed (1978).

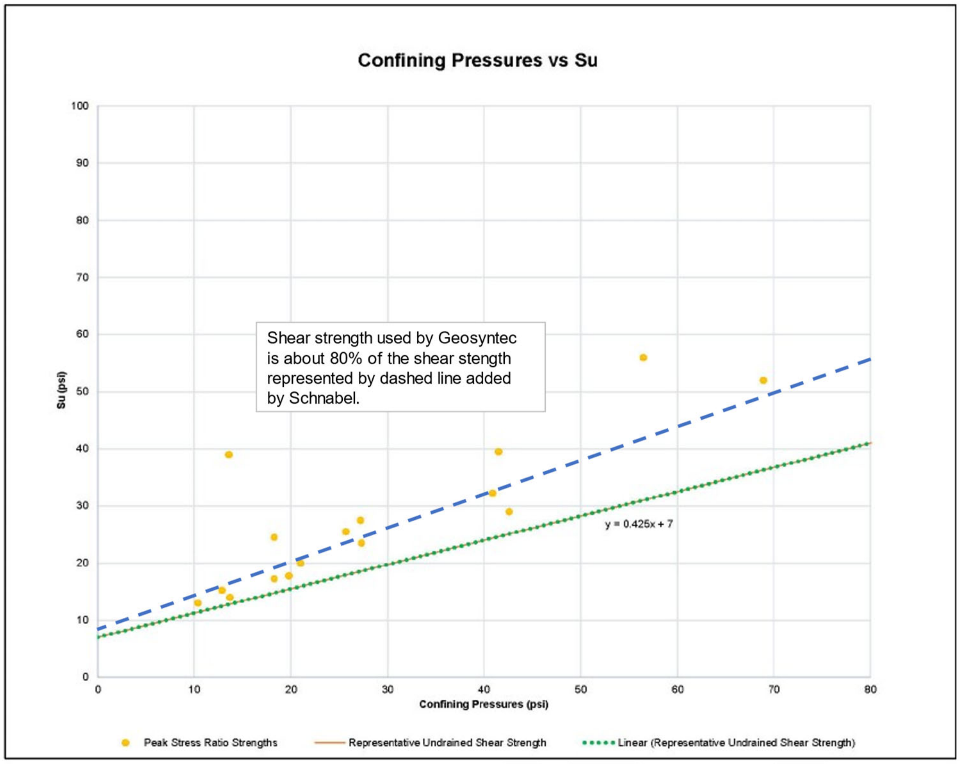

Figure 3: Undrained Shear Strength Characterization

5.5 Liquefaction and Cyclic Softening Hazards

5.5.1 Geosyntec Approach

Geosyntec did not mention liquefaction or cyclic softening in their report.

5.5.2 Discussion

Liquefaction and cyclic softening should be considered for completeness because they are significant mechanisms for large seismic slope displacement and are not captured in the pseudostatic or simplified seismic slope displacement analyses. In our opinion, the potential for either to be triggered due to the design ground motion may be low or negligible based on our cursory review of the boring logs included in the report.

5.6 Pseudostatic Factor of Safety

5.6.1 Geosyntec's Results

Geosyntec's pseudostatic analyses resulted in FS of 1.5 and 2.4 for the downstream and upstream slopes, respectively, both using k_s of 0.054 and displacement of 60 cm (2 feet). Geosyntec identified that the SDP criteria for FS of 1.1 was achieved with a k_s value of 0.16 (only the downstream slope was evaluated) and a k_s value of 0.2 was required to reduce the FS to 1.0 (only the downstream slope was evaluated). The estimated seismic displacement is less than 10 cm (4 inches) for k_s of both 0.16 and 0.2 (at the 98th percentile level).

5.6.2 Discussion

The results indicate that the dam meets the SDP requirements for the assumed design k_s of 0.054 with displacement of 60 cm (2 feet). This amount of displacement may be tolerable for the dam, and the SDP should confirm this in finalization of their review. Furthermore, Geosyntec's sensitivity analyses suggest a displacement of less than 10 cm (4 inches) at the minimum FS of 1.1 (i.e., with k_s of 0.16). This result indicates that the assessment would likely meet the requirements should the SDP consider a tolerable displacement level that is smaller than 60 cm (2 feet).

We agree that Geosyntec's assessment demonstrates compliance with the SDP requirements. However, we recommend a few actions be taken by SDP to finalize this assessment, as discussed in the following section.

6.0 CONCLUSION AND RECOMMENDATIONS

In conclusion, Schnabel is of the opinion that the approach adopted by Geosyntec is suitable for the project. Furthermore, Schnabel is of the opinion that the Geosyntec assessment complies with the minimum factor of safety for a seismic loading condition as defined by the SDP. We note that Geosyntec was intentionally conservative in multiple aspects of their analysis and despite this, the FS was calculated to be greater than 1.1. Geosyntec incorporated seismic displacement into their assessment, which is not a requirement of the SDP but greatly improves the overall assessment.

Although we agree with Geosyntec's conclusion, we recommend that the SDP consider the following before accepting the seismic slope stability assessment:

1. Assess the susceptibility and potential for triggering liquefaction and cyclic softening and evaluate their impact on dam stability if they are deemed likely to occur. This is important because liquefaction and cyclic softening are significant mechanisms for large seismic slope displacement that are not captured in the pseudostatic or simplified seismic slope displacement analyses.
2. Assess potential for seismic densification or post-liquefaction reconsolidation settlement, neither of which is captured in the pseudostatic or simplified seismic slope displacement analyses.
3. Verify the dam can tolerate up to 60 cm (2 feet) of permanent seismic displacement at the 2475-year return period hazard level (i.e., consistent with Geosyntec's assumption in developing their design-level analysis with k_s of 0.054) or provide Geosyntec an alternate allowable seismic slope displacement to consider.

The SDP may want to update the seismic stability assessment using the upcoming 2023 USGS NSHM because of its imminent public release. In doing so, various aspects of the assessment could also be explored, such as:

1. Consider site class C/D as well as D.
2. Consider a range of return periods, including 2475-years.
3. Consider source-specific Mw.
4. Use the recent displacement model of Bray and Macedo (2019).
5. Incorporate σ in the ε term used in the displacement model.

7.0 CLOSURE

We have endeavored to prepare this report in accordance with generally accepted geotechnical engineering practice and make no warranties, either express or implied, as to the professional advice provided under the terms of our agreement and included in this report.

We appreciate the opportunity to be of service for this project. Please contact either of the undersigned if clarification is needed for any aspect of this report.

Sincerely,

SCHNABEL ENGINEERING, LLC

James Dismuke, PE, GE
Senior Associate

Joseph S. Monroe, PE
Principal

JND:JSM

DOCUMENT1

References

Bray, J. D., and Macedo, J. (2019). Procedure for estimating shear-induced seismic slope displacement for shallow crustal earthquakes. *Journal of Geotechnical and Geoenvironmental engineering*, *145*(12), 04019106.

Bray, J. D., and Travasarou, T. (2007). Simplified procedure for estimating earthquake-induced deviatoric slope displacements. *Journal of geotechnical and geoenvironmental engineering*, *133*(4), 381-392.

Bray, J. D., and Travasarou, T. (2009). Pseudostatic coefficient for use in simplified seismic slope stability evaluation. *Journal of geotechnical and geoenvironmental engineering*, *135*(9), 1336-1340.

Duncan, J. M., and Wright, S. G. (2005). *Soil strength and slope stability*. John Wiley and Sons.

Hynes-Griffin, M. E., and Franklin, A. G. (1984). Rationalizing the seismic coefficient method. *Miscellaneous Paper GL-84-13, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MI*.

Makdisi, F. I., and Seed, H. B. (1978). Simplified procedure for estimating dam and embankment earthquake-induced deformations. *Journal of the Geotechnical Engineering Division*, *104*(7), 849-867.