SEISMIC STABILITY EVALUATIONS OF CHESBRO, LENIHAN, STEVENS CREEK, AND UVAS DAMS (SSE2)

PHASE A: STEVENS CREEK AND LENIHAN DAMS

LENIHAN DAM

COMPILATION REPORT
(REPORT No. SSE2A-LN)

Prepared for

SANTA CLARA VALLEY WATER DISTRICT
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TERRA / GeoPentech
a Joint Venture

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1.0 INTRODUCTION

In May 2010, the Santa Clara Valley Water District (District) retained Terra / GeoPentech (TGP), a joint venture of Terra Engineers, Inc. and GeoPentech, Inc., to complete seismic stability evaluations of Chesbro, Lenihan, Stevens Creek and Uvas Dams. These evaluations were required by the Division of Safety of Dams (DSOD) in June 2008 as part of their Phase III screening process of the State's dams located in highly seismic environments. The evaluations are also a vital part of the District's Dam Safety Program (DSP). Phase A of the project includes work on Stevens Creek and Lenihan Dams while Phase B includes work on Chesbro and Uvas Dams. The general scope of the project consists of the field, laboratory, and office studies required to evaluate the seismic stability of the four referenced dams.

This compilation report documents the results of our seismic stability evaluation of James J. Lenihan Dam (Lenihan Dam). The various aspects of the evaluation have been documented in several deliverables that were submitted to the District and to the Division of Safety of Dams (DSOD) as the evaluation efforts proceeded. The purpose of the compilation report is to provide a compendium of the various project deliverables preceded by an overview of the work performed highlighting the key aspects and findings of the seismic stability evaluation.

There were five project deliverables supporting the seismic stability evaluation of the dam:

1. Initial Review of Available Data for Lenihan Dam (Technical Memorandum SSE-TM-1LN)
2. Work Plan for Site Investigations and Laboratory Testing (Report No. LN-1)
3. Site Investigations and Laboratory Testing – Data Report (Report No. LN-2)
4. Site Characterization, Material Properties, and Ground Motions (Report No. LN-3)
5. Engineering Analyses (Report No. LN-4)

Each of these deliverables can be found after each numbered tab following this overview and are briefly summarized in the sections below.

2.0 GENERAL DESCRIPTION OF LENIHAN DAM

Lenihan Dam (formerly called Lexington Dam) is located in Santa Clara County, California, about 1 mile south of the City of Los Gatos. The dam is an earthfill structure that was constructed across Los Gatos Creek in 1952. The dam impounds Lexington Reservoir, which has a maximum capacity of 19,044 acre-feet at the spillway elevation of 653 feet[1]. DSOD has classified Lenihan Dam as a "High Hazard" dam because of the "extensive urban development in close proximity of the dam", with a DSOD Hazard Classification Total Class Weight of 30.

Appurtenant structures include a concrete-lined ogee-type spillway located in the left abutment and an outlet tunnel through the right abutment connected to an inclined inlet structure in the reservoir, on the upstream side of the right abutment, and to an outlet structure that allows reservoir water to discharge into Los Gatos Creek approximately 150 feet beyond the toe of the dam. The outlet tunnel and inclined inlet structure were completed in 2009 and replaced the

[1] Unless otherwise noted in this document, all elevations are referenced to NAVD88 vertical datum.

original outlet pipe that generally followed the preconstruction thalweg of Los Gatos Creek beneath the dam. The original outlet pipe was filled with grout and abandoned in place in 2009.

Figure 1 contains transverse sections through the current configuration of the dam at Stations 14+10 and 15+95 that are representative of dam zoning and conditions near the center of the valley. The locations of the two sections are shown on the insert in the lower portion of the figure. As shown on Figure 1, Lenihan Dam was constructed as a compacted earth dam with upstream and downstream shells, core and drainage zones. The core is further divided into the upper core and lower core to reflect significant differences in material properties above and below elevation 590 feet. The dam is about 195 feet high as measured from the lowest point in the foundation beneath the crest, and about 207 feet high as measured from the lowest point of the downstream toe to the crest.

3.0 INITIAL REVIEW OF AVAILABLE DATA – TAB 1

At the onset of the seismic stability evaluation we discovered that there was an enormous amount of available geotechnical information at Lenihan Dam from previous investigations and from geotechnical instrumentation being monitored at the dam. Our initial review of the available data led to the following conclusions:

1. The data strongly indicated that the dam was constructed on bedrock; i.e., no soil was left in place beneath the dam. This was a very significant and positive finding from a dam safety perspective because it meant that potential liquefaction of soils left in place beneath the dam was not an issue.
2. There appeared to be sufficient information available to define the geometry of the dam and of its foundation.
3. A detailed review and thorough evaluation of the available data on the properties of the various zones of the embankment (as indicated by the construction records, field investigations and laboratory tests completed to date) might provide most of the information necessary to support the engineering analyses.

Our initial review of the available data was documented in a Technical Memorandum located behind Tab 1. Based on this review, we recommended to the District (and they concurred) that we proceed with an interim site characterization based on the wealth of existing data, perform preliminary engineering analyses using this interim site characterization data, identify what supplemental field and laboratory data were necessary to reduce the uncertainties in the results of the seismic stability analyses of the dam, and prepare a work plan for a field and laboratory investigation to obtain these data. This approach was intended to maximize the use of the available information and to better focus any supplemental investigations.

4.0 INTERIM SITE CHARACTERIZATION AND PRELIMINARY ENGINEERING ANALYSES – TAB 2

We proceeded with an interim site characterization based on the data available from the dam construction records and the previously completed field investigations and laboratory tests. This site characterization included site geology (regional and local conditions), foundation conditions at the dam, characterization of the general nature of the embankment materials, and determination of index properties and engineering properties of the materials that were relevant to the engineering analyses of seismic deformations.

In addition, preliminary engineering analyses using the interim site characterization were performed to identify data gaps. The seismic response of Lenihan Dam had been recorded during the Loma Prieta earthquake by three accelerographs (two on the dam crest and one on the abutment). This set of recordings and the information on the seismic performance of the dam at that time provided an opportunity to not only assess the appropriateness of the material properties developed based on existing information and make adjustments to these properties, as necessary, but also to calibrate the FLAC-based seismic deformation model(s) that would be used in the seismic evaluation of the dam under the design earthquake shaking conditions. The results of the preliminary engineering analyses were then used to identify key material parameters and material zones that warranted further refinement.

The results of the interim site characterization and preliminary engineering analyses were documented in Report No. LN-1 (found behind Tab 2) that concluded with a work plan for supplemental field investigations and laboratory testing.

5.0 SUPPLEMENTAL FIELD INVESTIGATIONS AND LABORATORY TESTING – TAB 3

The supplemental investigations were aimed at:

1. better characterizing the undrained shear strength and stress-strain behavior of the various embankment zones of the dam for direct simple shear loading, and the variation of shear strengths within each of the zones;
2. evaluating the stiffness of the embankment materials, as indicated by the shear wave velocity of the materials; and
3. better defining the difference in shear wave velocities between the soft and hard rock found in the Franciscan Complex bedrock foundation that may influence the input ground motions.

Our approach for obtaining the data required for Item 1 was to collect intact samples of embankment materials with a 4-inch diameter Pitcher Barrel Sampler in mud rotary borings and to test these samples in the laboratory using undrained shear strength tests with pore pressure measurements for triaxial compression and direct simple shear loading conditions. The laboratory engineering property tests were complemented by measurements of grain size, water content, and Atterberg Limits. Cone Penetrometer Test (CPT) probes were completed at potential locations of mud rotary boreholes before these boreholes were drilled, and the data from these CPT probes were used to finalize the boring locations and identify depths within the mud rotary borings where the presence of gravel in the embankment appeared to be less likely. These depths were targeted for obtaining good quality Pitcher Barrel samples. This was an important role for the use of the CPT data because the experience from past geotechnical investigations was that the gravel content of the embankment materials made obtaining good quality Pitcher Barrel samples very difficult.

Our approach for obtaining shear wave velocity measurements within the embankment soils and underlying bedrock, to provide the data required for Items 2 and 3 above, was to perform OYO

P-S Borehole Suspension Logging in the mud rotary borings. In addition, downhole geophysical logging using the "seismic cone" was performed as part of the CPT sounding work to provide additional measurements of shear wave velocity.

The originally recommended scope of the field investigations included two mud rotary borings and ten CPT probes. It also included Multisource Spectral Analysis of Surface Wave (MSASW) geophysical survey lines to evaluate the variation of shear wave velocity along survey lines that crossed boundaries between soft and hard rock within the Franciscan Complex. However, after review and discussion of the proposed program with DSOD, the program was modified as follows:

6. The number of mud rotary borings was increased from two to three;
7. The number of CPT probes was reduced from ten to four; and
8. The MSASW lines were eliminated.

The data collected during the supplemental field investigation and laboratory testing program are documented in a Data Report (Report No. LN-2) found behind Tab 3.

6.0 SITE CHARACTERIZATION AND MATERIAL PROPERTIES – TAB 4

The results of the supplemental field investigations and laboratory testing were interpreted and combined with the results of the interim site characterization to summarize the geology of the site, describe the conditions of the dam and foundation, and characterize the material properties to be used in the engineering analyses for the seismic stability evaluation of the dam. The results of this effort are documented in Report No. LN-3 found behind Tab 4.

The key findings of the site characterization are as follows:

1. The dam is founded directly on bedrock – no alluvial or colluvial soils were left in place beneath the embankment.
2. The geometry of the valley where the dam was constructed is complex. The right side of the valley (looking downstream) has a relatively uniform side slope but the left side of the valley is characterized by a massive knob of bedrock that underlies the upstream portion of the dam.
3. With the exception of the internal drainage zones, all embankment materials are well-compacted soils with varying amounts of sand and gravel in a clay matrix.
4. Except for the drain materials, the embankment soils have very low permeabilities.
5. There are no liquefiable materials within the dam or its foundation.

The generalized geometry and material classifications of the dam at its maximum section are shown on Figure 2. This figure has been excerpted from Report No. LN-3 for ease of reference for the reader of this overview. The key findings related to material properties are as follows:

1. The source of materials for the construction of the upstream shell and upper core of the dam is the Franciscan Complex mélange from borrow areas located just upstream of the upstream toe of the dam. The physical/index properties and the engineering properties of these two zones are very similar.

2. The source of the materials used in the construction of the lower core is clayey alluvial/colluvial fan deposits from borrow areas at the mouth of Limekiln Canyon upstream of the dam on the right side of the valley. The lower core material is a clay of high plasticity; it contains little to no gravel and has a lower strength than the upper core and upstream shell.
3. The source of the materials for the construction of the downstream shell is Franciscan Complex sandstone and mélange excavated during construction of the spillway channel. The physical/index properties of the downstream shell are similar to those of the upstream shell and upper core except that the gravel content is higher than in those two other zones. The strength of the downstream shell materials is quite variable and appears to be, on average, lower than the strength of the upstream shell and upper core.

7.0 GROUND MOTIONS – TAB 4

Site-specific input ground motions were developed for use in the seismic deformation analyses, as documented in Report No. LN-3 (Tab 4).

Key elements in the development of these site specific ground motions are as follows:

1. Lenihan Dam is classified as a "high consequence" dam by DSOD, based on a DSOD Hazard Classification Total Class Weight of 30.
2. The two seismogenic faults controlling the seismic hazard at the dam are the Stanford-Monte Vista and San Andreas faults. The Stanford-Monte Vista event controls the shaking condition at the site for periods of 1 second or less for the lower magnitude earthquake scenario. The San Andreas event has a larger earthquake magnitude and controls the shaking condition at the site for periods larger than about 1 second.
3. The average shear wave velocity within the upper 30 meters of the dam foundation rock, V_{S30}, was calculated based on OYO shear wave velocity data collected at two locations beneath the dam and one location within close proximity of the dam. A site-specific V_{S30} of 1,260 m/sec was determined based on these measurements and used in the development of the design response spectra for the Stanford-Monte Vista and San Andreas events.
4. Three seed time histories were selected for the Stanford-Monte Vista event and adjusted to match the target response spectra. It should be noted that the Arias Intensity values of the three selected ground motions exceed the best estimate of Arias Intensity provided by the Watson-Lamprey and Abrahamson relationship with 84th percentile ground motion inputs.
5. Seed time histories for the San Andreas event were selected through a multi-step screening of the PEER Ground Motion Database. The selection process screened all 3,551 records in the Database and yielded eight records with values of Arias Intensity and significant duration similar to those of the San Andreas event. These eight records, as well as the Denali TAPS record, were chosen and evaluated, and three final seed time histories were selected. The final three selected seed time histories were then adjusted to match the target response spectra. As for the Stanford-Monte Vista event, the Arias Intensity values of the three ground motions exceed the best estimate of Arias Intensity provided by the Watson-Lamprey and Abrahamson relationship with 84^{th} percentile ground motion inputs.

8.0 ENGINEERING ANALYSES – TAB 5

The purpose of the engineering analyses was to evaluate the seismic stability of the dam during the Maximum Credible Earthquake (MCE) and to assess the seismic deformations of the structure as a result of the MCE. To that end, the scope of the analyses included the following:

1. seepage analyses to establish total heads and pore-water pressures associated with steady state seepage;
2. static and pseudo-static stability analyses; and
3. non-linear dynamic analyses of seismic deformations.

In addition to the evaluation of the seismic response of the dam to the MCE, the non-linear deformation analyses also included an evaluation of the seismic performance of the dam during the Loma Prieta earthquake of 1989 using the motion recorded at the left abutment of the dam as the input ground motion.

The engineering analyses were based on the site characterization, material properties, and ground motions discussed above and documented in Report No. LN-3 (Tab 4). The results of the analyses are contained in Report No. LN-4 that is found behind Tab 5. Key findings from the analyses are summarized below.

The finite element seepage analyses showed good agreement between measured piezometric levels and calculated total heads and provided a reliable basis for defining pore-water pressures for stability and seismic deformation analyses.

The Factors of Safety were found to be 2.1 and 2.6 for static steady state seepage under full reservoir and for rapid drawdown conditions, respectively; these values exceed the minimum required values of 1.5 and 1.3, respectively, specified by the US Army Corps of Engineers.

The yield accelerations from pseudo-static loading of the dam under full reservoir level and steady state conditions were estimated at 0.23g and 0.33g for the downstream slope and upstream slope, respectively.

The results of the seismic deformation analyses indicated the following:

1. For the evaluation of the potential for the loss of freeboard, one can conservatively use a vertical crest settlement of about 1-1/2 feet and a horizontal downstream movement of about 1 foot. The estimated crest settlement includes the estimated vertical movement from the FLAC analyses plus an additional allowance of about 1 foot to account for earthquake-induced vertical movements that may be underestimated by the FLAC analyses.
2. The seismic deformations of the embankment elsewhere should be relatively small, but some locally larger seismic deformations (less than a few feet) may be possible. However, it is highly unlikely that these locally larger seismic deformations will affect the integrity of the dam.
3. Because the values of seismically-induced displacements from the MCE evaluation events are relatively small, the likelihood of significant cracks forming in the crest and other areas is considered very low. Furthermore, even if some cracks form, they would likely be shallow

longitudinal cracks of limited extent, and not more serious than the cracking observed during the Loma Prieta event.

The results of the FLAC analyses for the six evaluation ground motions that represent the MCE indicated that the permanent seismic deformations of the dam are only slightly higher than the deformations measured during the Loma Prieta event. The overall similarity of the calculated seismic displacements and seismic responses may be in part due to the similarity of the spectral values of the input motions in the period range near the fundamental period of the embankment. The QUAD4MU and Equivalent Linear FLAC analyses indicated that the fundamental period of the embankment under these shaking conditions is about 1 second and the response spectral values of the Loma Prieta ground motion for this site are in fact slightly higher than those of the MCE evaluation ground motions for a period in the vicinity of 1 second.

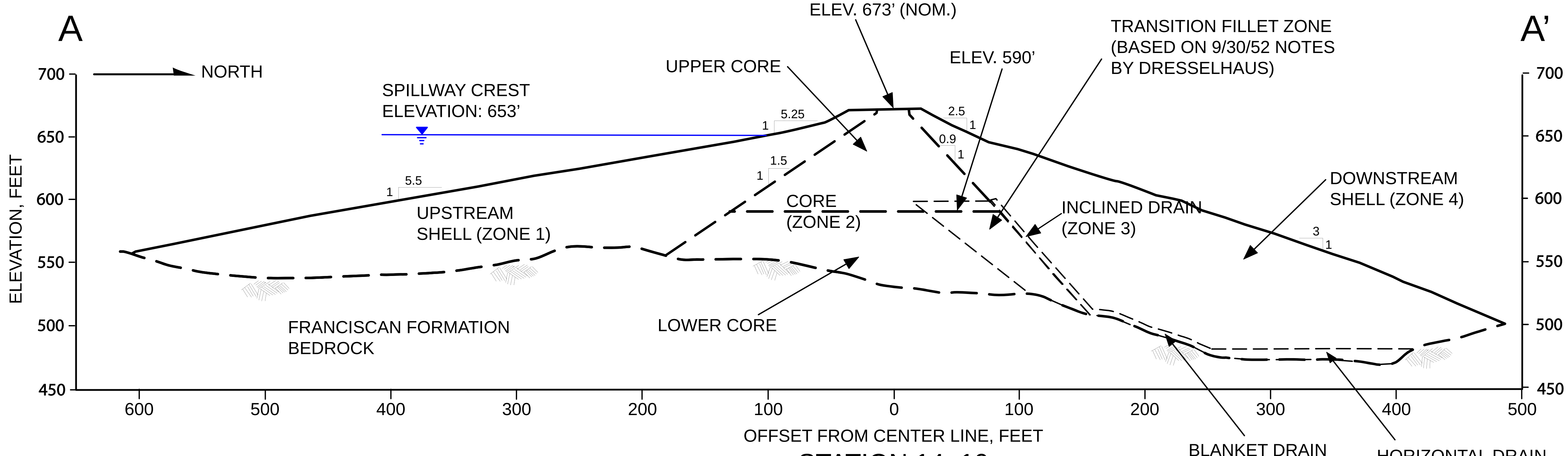
To test the reasonableness of the seismic deformation estimates resulting from the FLAC analyses, both simplified Newmark-type analyses and a full Newmark-type analysis were used to estimate displacements based on yield accelerations and the MCE evaluation ground motions. The estimates from these Newmark-type methods fall within the range of displacements estimated using FLAC and confirm the reasonableness of the FLAC results.

9.0 CONCLUSIONS AND RECOMMENDATIONS

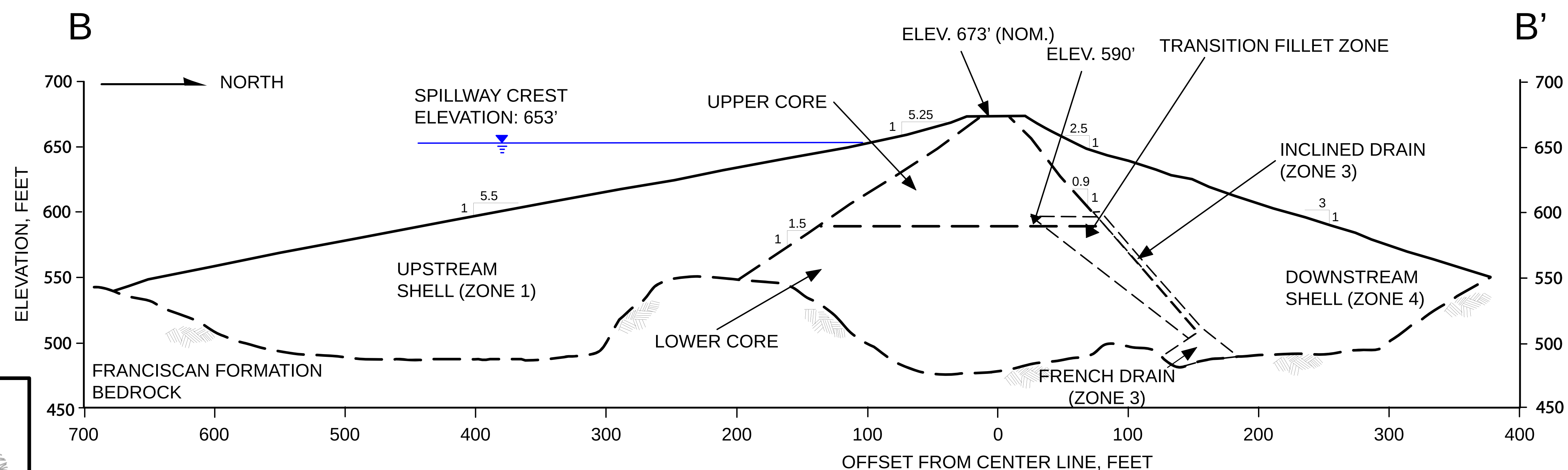
Our engineering analyses indicate that Lenihan Dam will perform well when subjected to the evaluation ground motions that represent the MCE. Maximum crest settlements of about 1 ½ feet and horizontal downstream movement of about 1 foot have been estimated. The likelihood of significant cracks forming in the crest and other areas is considered very low. As a result, we have concluded that no seismic remedial measures are necessary at Lenihan Dam.

DSOD reviewed our work and also performed independent analyses of the seismic deformations of the dam. In a letter to the District dated November 1, 2012, DSOD indicated that, based on their analyses, the dam could experience up to five feet of settlement as a result of the MCE but that this performance was satisfactory to them given "the available freeboard, embankment design, and material characteristics". Therefore, they agreed with our conclusion that the dam did not require seismic remediation.

Based on the result of our seismic stability evaluation, we recommend that piezometric levels, vertical and lateral movements, and seepage flows continue to be monitored and evaluated to assure the continued safe operation of the dam. We also recommend that the condition of the dam be inspected immediately following future earthquakes to check that movements and cracking are consistent with those expected based on our engineering analyses and/or DSOD's independent analyses.



STATION 14+10



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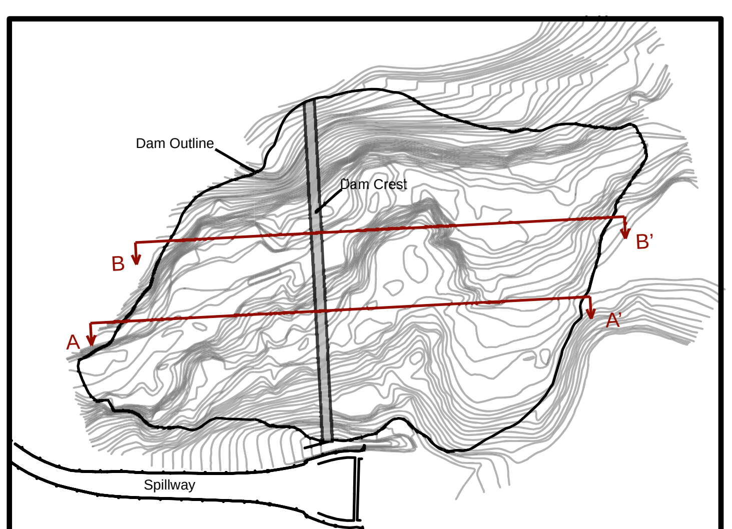

TERRA / GeoPentech a Joint Venture	CROSS SECTIONS LENIHAN DAM SEISMIC STABILITY EVALUATIONS (SSE2)	Figure 1

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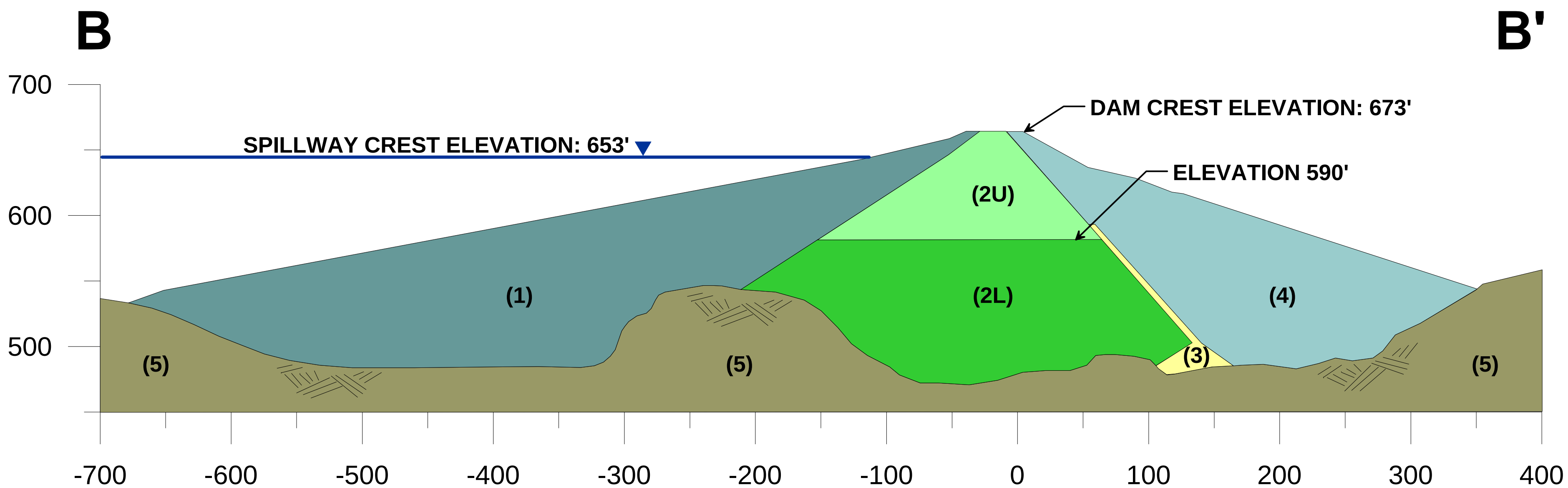

Zone	Color Code	Material Description	Predominant Soil Classification
1		Upstream Shell	Gravely Clayey Sands (SC) to Sandy Clays (CL)
2U		Upper Core (Above El. 590)	Gravely Clayey Sands (SC) to Clayey Gravels (GC)
2L		Lower Core (Below El. 590)	Sandy Highly Plastic Clays (CH) to Silty Sands-Sandy Highly Plastic Silts (SM-MH)
3		Drain Material	N/A
4		Downstream Shell	Gravely Clayey Sands (SC) to Clayey Gravels (GC)
5		Bedrock	Franciscan Complex

Note: See insert on Figure 1 for location of Section B-B'

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IDEALIZED GEOMETRY OF MAXIMUM CROSS SECTION - LENIHAN DAM

SEISMIC STABILITY EVALUATIONS (SSE2)

Figure 2

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