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Estimating Seismic Settlements from Liquefaction and Cyclic Softening and Their Impact to Design of a School Building

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ESTIMATING SEISMIC SETTLEMENTS FROM LIQUEFACTION AND CYCLIC SOFTENING AND THEIR IMPACT TO DESIGN OF A SCHOOL BUILDING

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ABSTRACT

Estimation of static and seismic settlements is critical for the design of a structure to assess whether the structure can tolerate given levels of total and differential settlements and angular distortion. The design of a public school building required the estimation of both liquefaction-induced settlement due to the presence of a potentially liquefiable layer, and settlement from cyclic softening of soft clay layers. Tolerable levels of differential settlements for the proposed school building were not to exceed 2 inches across the building.

The soft clay had a plasticity index of 12, a liquid limit of 32, and SPT blow counts of less than 4. Recent publications do not consider this clay potentially liquefiable, but consider it susceptible to cyclic softening. In addition to the borings, in-situ vane shear testing and CPT soundings were conducted at the site to supplement the data for our analysis.

Using published methods we conducted an assessment of the soft clay and calculated factors of safety against cyclic softening as low as 0.0. In-situ vane shear testing resulted in soil sensitivities ranging from 1.6 to 3.4. Using CPT data we conducted a cyclic softening analysis of the entire soil column to a depth of about 50 feet.

This paper describes the encountered site conditions, methodology for estimating both seismic and static settlements, criteria for acceptable foundation performance, importance of evaluation of cyclic softening of soft clay layers, and the challenges working with the regulatory agency. The results of our analyses indicate differential settlements of about 2 inches.

INTRODUCTION

Two new buildings, including an administration building and a gymnasium, are proposed for an existing public elementary school campus located in the Central Valley of California, USA. Both buildings are to be single-story, steel-framed modular structures with slab-on-grade floors and conventional spread footings.

As required by state law, a seismic hazard assessment was conducted for the proposed buildings. The ground motion analysis consisted of both probabilistic and deterministic analyses using maximum rotated motions and attenuation relationships developed by Boore and Atkinson (2008), Campbell and Bozorgnia (2008) and Chiou and Youngs (2008). The resulting ground motions were used to estimate seismic settlement due to liquefaction.

Challenges were encountered during the regulatory agency review process due to the presence of soft, low to medium plasticity clays identified as borderline liquefiable according to Seed et al. (2003) and Bray and Sancio (2006), and non-liquefiable according to Idriss and Boulanger (2008). Additionally, the reviewers requested an evaluation for the potential for cyclic softening of soft clays encountered at the site. A cyclic softening analysis was conducted using methods presented by Idriss and Boulanger (2008), and Robertson (2009) for the borings and cone penetration tests (CPT), respectively.

Supplemental explorations and laboratory soil testing were required to justify the results of the analyses and the conclusions presented for total and differential seismic settlement. In addition, in situ vane shear testing was conducted to evaluate soil sensitivity.

This paper presents the results of our seismic settlement analyses and the difficulties encountered working with the regulatory agency to obtain project approval.

GEOLOGIC SETTING

The school site lies within the central portion of the Great Valley geomorphic province of California. The province is bordered to the north by the Cascade Range and Klamath Mountains, to the west by the structurally complex sedimentary and volcanic rock units of the Coast Ranges, to the east by the granitic and metamorphic basement rocks which form the gently sloping western foothills of the Sierra Nevada Mountains, and to the south by the east-west trending Transverse Ranges. About 645 km long and 80 km wide, the Great Valley is an asymmetrical, synclinal trough formed by tilting of the Sierran block during the late Tertiary and Quaternary periods with the western side dropping to form the valley and the eastern side uplifting to form the Sierra Nevada Mountains. Within the project area, erosion of the adjacent Sierra Nevada Mountains and Coast Ranges has in-filled this valley with a thick sequence of unconsolidated to semi-consolidated Quaternary (Pleistocene and Holocene) age alluvial, basin, and delta plain sediments deposited by the Sacramento and San Joaquin Rivers and their tributaries. The thickness of the valley sediments varies from a thin veneer at the edges of the valley to thousands of meters in the western portion. The bedrock complex is likely composed of metamorphosed marine sediments similar to those found in the foothills of the western Sierra Nevada Mountains and the core of the Coast Ranges.

The portion of the valley in the study area exhibits a fairly complete stratigraphic section of Cretaceous, Tertiary, and Quaternary deposits. The sediments deposited prior to mid-Tertiary time were in a marine environment. Changes in sea level, valley filling, and uplift resulted in deposition of sediments in a continental environment after mid-Tertiary time. These continental sediments are exposed at the surface in the study area. The near-surface sediments at the school site have been deposited by streams emanating from the mountains as debris flows, hyperconcentrated mudflows, or braided stream flows (Knudsen and Lettis, 1997). Various authors have mapped the local geology of the area, such as Brabb, et al. (1997), and Wagner, et al. (1990). These maps differ in scale and detail but agree that the site is located within weakly consolidated Holocene alluvial fan deposits. This unit is described as moderately to poorly sorted, and moderately to poorly bedded clay, silt, sand, and gravel.

SUBSURFACE EXPLORATIONS

Four subsurface investigations were conducted to accurately characterize the subsurface conditions at the site. The initial subsurface exploration plan called for drilling four soil borings to depths ranging from 10 to 50 feet below existing site grade. At the time of the initial exploration, much of the footprint of the proposed buildings was occupied by existing structures. Boring B-1 was located as close as possible to both proposed buildings, within the space available that could fit a truck mounted drill rig. It was drilled using the rotary wash method to a depth of approximately 50 feet, and was intended to be used for the seismic settlement analysis for the entire site. The other three borings (B-2 through B-4) were drilled to depths ranging from 10 to 15 feet below existing site grade, using hollow stem augers. They were drilled at accessible locations throughout the site to assess vertical and lateral variability of the subsurface conditions.

Based on the borings drilled at the site, the subsurface soils generally consisted of very soft to firm silt and clay distal fan deposits to depths ranging from about 10 to 15 feet below grade. These soils were underlain by alluvial deposits consisting of discontinuous and interbedded layers of loose to medium dense sand, and very soft to stiff silt and clay. The soils encountered in one of the borings (boring B-3) differed from the other borings in that clayey sands were encountered from the surface to a depth of about 16 feet below ground surface. Clean sand was encountered in the deepest sample and in the sampler shoe of boring B-3 at a maximum depth of about 16½ feet below ground surface. Groundwater was initially encountered at a depth of about 15 feet then rose to a final depth of about 9 feet.

Prior to submission of the investigative report to the regulatory agency, a second subsurface investigation was conducted. For this investigation, a CPT was advanced to a depth of about 50 feet below ground surface. The CPT was located within the footprint of the proposed gymnasium. The CPT data was used to supplement the boring data that was used in the preliminary seismic settlement calculations. The CPT data was consistent with the boring data, indicating about 15 feet of firm to soft clay underlain by interbedded layers of loose to medium dense sand and silt, and stiff clay.

The third subsurface investigation at the site was conducted, at the suggestion of the regulatory agency, to provide additional supporting data for the seismic settlement calculations and conclusions. The investigation consisted of a CPT (CPT-2), advanced to a depth of about 50 feet, and a boring (B-5) drilled to a depth of about 50 feet. In addition, in situ vane shear testing was conducted at various depths within the borehole using an Acker Vane Shear device. The boring and CPT generally agreed with the other explorations, indicating soft clay between depths of about 10 to 17 feet, underlain by loose sand to about 21.5 feet.

Finally, the fourth investigation included a third CPT (CPT-3) to a depth of about 50 feet. This investigation was conducted to confirm the subsurface conditions encountered in boring B-3. The soils encountered in boring B-3 differed from the soils encountered in all other explorations. CPT-3 indicated the presence of clay to a depth of about 10 feet, underlain by about 5 feet of silt, followed by about 7 feet of sand. The soils below a depth of about 22 feet were similar to the other explorations, consisting of interbedded layers of medium dense to dense sand, silt and clay.

Figure 1 shows the locations of the explorations, in relation to the footprints of the proposed buildings.

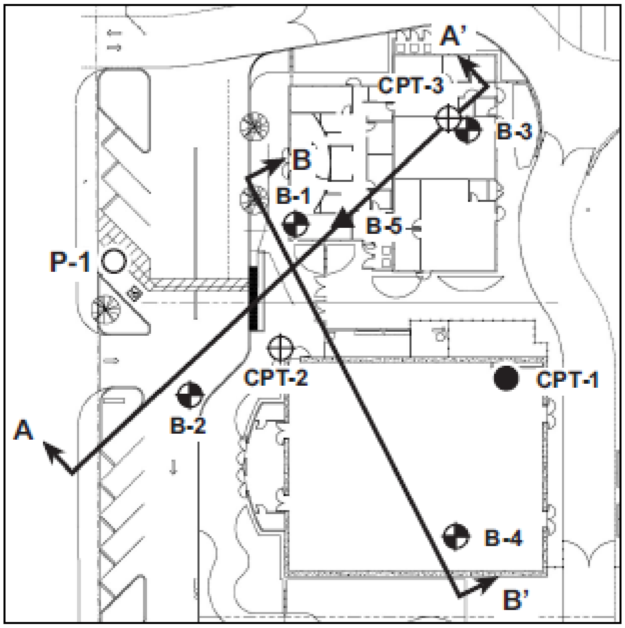

Fig. 1. Subsurface exploration map.

LABORATORY AND FIELD TESTING

Laboratory Testing

Laboratory tests were performed on selected soil samples to evaluate their physical characteristics and engineering properties. The laboratory testing program included sieve analyses on potentially liquefiable material, and Atterberg limits and moisture content testing on soft clays. The results of the laboratory testing are presented in Table 1.

Table 1. Laboratory Test Results

Boring No.	Depth (feet)	USCS	Moisture Content (% of dry weight)	Percent passing #200 sieve	Atterberg Limits	
					PI	LL
B-1	0.0	CL			19	33
	5.0	ML		13		
	10.0	CL		94	12	32
	20.0	SW-SM		13		
	25.0	CL		95	23	42
	35.0	ML		89	4	22
B-2	5.5	CL	21			
B-3	3.0	SC	13			
B-4	5.0	CL	21			
	10.5		24			
B-5	12	CL	30			
	16.5	CL	34		12	32
	22	CL	27	95	28	45
	38	CL-ML		82		
	45.5	CL-ML	26		7	29

The sieve analyses indicated potentially liquefiable coarse grained soils at about 20 to 25 feet in boring B-1. Similar coarse grained soils were encountered in boring B-5, but were not tested for fines content. Based on the Atterberg limits testing, the fine grained soils at 10 to 20 feet in borings B-1 and B-5 are considered to be borderline potentially liquefiable (sand-like behavior) according to Seed et al. (2003) and non-liquefiable (clay-like behavior) according to Idriss and Boulanger (2008).

Field Testing

In situ vane shear testing was conducted at various depths in boring B-5. The testing was done using an Acker Vane Shear device to determine in situ and remolded shear strengths. Table 2 presents the results of the vane shear testing.

Table 2. Vane Shear Test Results

Depth (feet)	Shear Strength (psf)	Remolded Shear Strength (psf)
10	932	482
14	1,150	342
24	1,830	1,117

SEISMIC SETTLEMENT ANALYSES

Allowable maximum total and differential settlement for the proposed buildings were established by the structural engineer and the regulatory agency. Initially, total settlement was not to exceed 6 inches; however, later on, it was made clear that total settlement was not the major concern and higher values could be accommodated. Differential settlement was not to exceed 2 inches across the building.

Initially only a liquefaction triggering analysis was conducted for the site. However, during the course of the investigation, it became apparent that cyclic softening of the clay layers could play a role in the seismic settlement of the structures. In addition, dry settlement due to seismic shaking was estimated for the site.

Liquefaction Analysis

A liquefaction triggering analysis was conducted for each of the 50 feet deep explorations, including borings B-1 and B-5, and CPTs CPT-1 through CPT-3. The analyses for liquefaction triggering and seismically-induced settlements were conducted using both Seed et al. (2003) and Idriss and Boulanger (2008) methods. Settlements for Seed et al. (2003) method were estimated using Cetin et al. (2009). The results of the analyses are presented in Table 3.

Table 3. Liquefaction-Induced Settlements Results

Exploration	Total Settlement (in)	
	Seed (2003)	Idriss and Boulanger (2004)
B-1	1.3	2.4
B-5	3.2	2.7
CPT-1	2.8	4
CPT-2	3.6	4.8
CPT-3	4.6	6

Cyclic Softening

A cyclic softening analysis was performed due to the presence of soft clay with plasticity indices outside the range considered liquefiable, based on both Seed et al.(2003) and Idriss and Boulanger (2008) methods, and according to Bray and Sancio (2006).

The cyclic softening analysis was conducted using the methods presented in Idriss, and Boulanger (2008) for the borings and in Robertson (2009) for the CPTs. Estimated soil sensitivities, using the liquidity index correlation to vertical effective stress, Figure 136 of Idriss and Boulanger (2008), indicated soils with sensitivities close to 8. Idriss and Boulanger (2008) suggest that soils with sensitivities greater than 8 may be susceptible to ground deformation due to cyclic softening. Soil sensitivities were again estimated after the final subsurface investigation using the vane shear data, and ranged from 1.6 to 3.3.

Factors of safety were calculated for cyclic softening of saturated clays with a 3 percent yield, equation 113 of Idriss and Boulanger (2008) using data from borings B-1, B-2, B-4 and B-5, and from CPT-1 through CPT-3. The borings indicated factors of safety less than 1 at the depths presented in Table 4.

Table 4. Cyclic Softening Factors of Safety

Boring	Depth	Factor of Safety
B-1	10	0.78
	15	0.27
	25	0.67
B-2	10.5	0.00
B-4	15.5	0.52
B-5	16.5	0.50
	21.5	0.96
	45	0.86

The approach presented by Idriss and Boulanger (2008) does not provide a method for calculating settlement without specialized laboratory testing. However, Robertson (2009) does provide a method for calculating settlement due to cyclic softening using CPT data. Factors of safety were calculated for each CPT using both the Idriss and Boulanger (2008) and Robertson (2009) methods. Settlement was then calculated using the calculated factors of safety and the method presented by Robertson (2009). The results for CPT-2 are presented in Fig. 2.

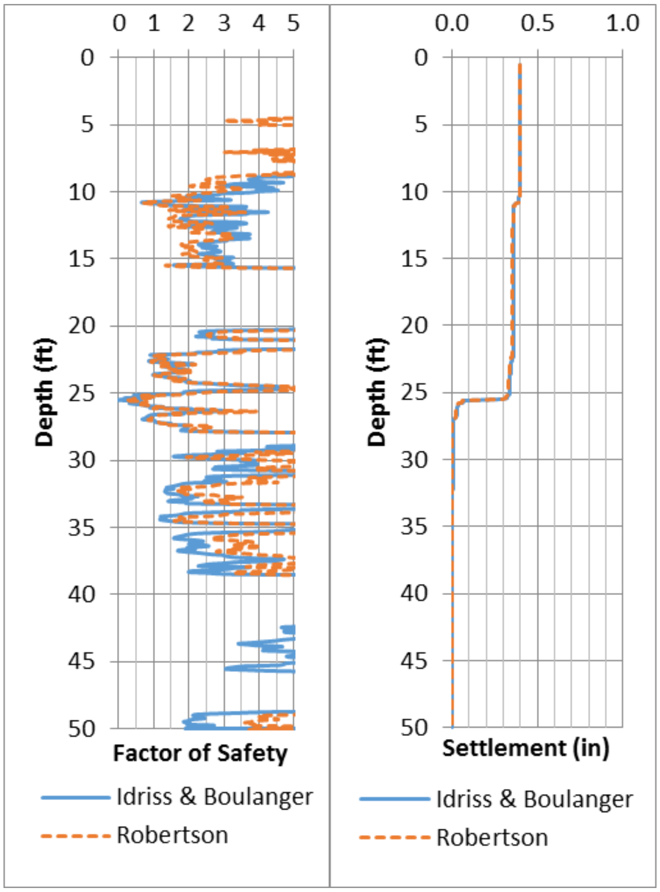

Fig. 2. Factors of Safety and Cumulative Settlement for

Cyclic Softening in CPT-2.

Although factors of safety differed somewhat between the two methods used, the settlement calculations returned very similar results. The same was true for CPT-1 and CPT-3, where cumulative settlement calculations resulted in negligible settlements.

Since settlement due to cyclic softening could not be directly calculated for the borings, it was estimated using the maximum volumetric strain calculated in the CPTs. The volumetric strain was calculated to be 0.40%. This was multiplied by the thickness of soil layers identified in the borings with a factor of safety below 1. Since the results of this estimate matched closely with the settlement calculations performed for the CPTs, the CPT values were used.

Additional data supporting the findings of minimal cumulative settlement were the estimated overconsolidation ratios (OCR) based on data from the CPTs. OCR was above 2 in CPT-1 and CPT-3. In CPT-2, OCR dropped below 1 at about 10 and 25 feet, the same depths where the factor of safety dropped below 1 and where potential settlement was identified.

Total and Differential Settlement

Total earthquake-induced settlement was calculated by adding the potential settlement due to liquefaction with the potential settlement due to cyclic softening, and the estimated dry seismic settlement at each exploration location. Both Cetin et al. (2009) and Idriss and Boulanger (2008) methods for calculation of liquefaction induced settlement were used; however, since the differences were minimal between both methods for calculating settlement due to cyclic softening, only the maximum values of settlement were used.

As can be seen in Table 5, total settlement calculated from the borings was consistently lower than total settlement calculated from the CPT data. The difference is likely due to the limited sampling and widely spaced data points in the borings. For this reason, and to prevent the introduction of error into the calculation, the differential settlement calculation did not mix boring and CPT data. Differential settlement was calculated by finding the maximum difference between total settlements at each exploration location for both the borings and the CPTs. Table 5 presents the results of the total and differential settlement calculations for the CPTs.

Table 5. CPT Total and Differential Seismic Settlements

		Settlement (in)	
	Exploration	Cetin et al. (2009)	Idriss and Boulanger (2008)
Liquefaction	CPT-1	2.8	4
	CPT-2	3.6	4.8
	CPT-3	4.6	6
Cyclic Softening	CPT-1	0	0
	CPT-2	0.4	0.4
	CPT-3	0	0
Dry Seismic Settlement using Tokimatsu and Seed (1987)		0.25	0.25
Total Settlement	CPT-1	3.05	4.25
	CPT-2	4.25	5.45
	CPT-3	4.85	6.25
Differential		1.8	2.0

Table 6 presents the total and differential settlements for the borings.

Table 6. Boring Total and Differential Seismic Settlement

		Settlement (in)	
	Exploration	Seed et al (2003)	Idriss and Boulanger (2008)
Liquefaction	B-1	1.3	2.4
	B-5	3.2	2.7
Cyclic Softening	Assumed for All	0.4	0.4
Dry Seismic Settlement using Tokimatsu and Seed (1987)		0.25	0.25
Total Settlement	B-1	1.95	3.05
	B-5	3.85	3.35
Differential		1.9	0.3

Based on these results, the total and differential settlements recommended for design were 6.25 and 2.0 inches, respectively. Since the proposed foundation system was a stiffened system of spread footings and grade beams, the differential settlement could be applied across the entire building.

REGULATORY AGENCY COMMENTS

The regulatory agency (RA) played a key role in pushing for additional field and laboratory data in order to develop a complete seismic settlement analysis across the entire site. As a result of RA comments and suggestions, two additional CPTs (CPT-2 and CPT-3) were advanced, and one additional boring (B-5) was drilled. CPT-1 was advanced as a pre-emptive strike to provide supporting data to the original report. In addition, the vane shear testing in boring B-5 was done to alleviate concerns by the RA regarding bearing capacity after an earthquake.

Initially, cyclic softening was not analyzed because the site is not located within a state or local agency designated seismic hazard zone, and such hazards are rarely encountered in the area. The initial cyclic softening analyses were not satisfactory to the RA because settlement estimates were only provided for CPT-1, which did not encounter the very soft clays encountered in boring B-1. CPT-2 did encounter the very soft clays and proved valuable to the final analysis. CPT-3 was advanced near the location of boring B-3 because the soil conditions at boring B-3 appeared to vary somewhat from the remainder of the explorations. The CPT indicated only slight variations from the other explorations. The differing conditions reported in boring B-3 may have been due to the use of hollow stem augers near groundwater, and the presence of a near-by buried utility line that may have introduced artificial fill at the boring location.

Another issue that the RA had with the analyses was the depth to groundwater that was used. Typically, the historical high groundwater depth is used in a liquefaction analysis. In this case, the nearest water well with complete historical data, dating back to the 1970's indicated groundwater at a historical high of about 4 feet below ground surface. However, groundwater was encountered in the borings at an initial depth of 15 feet, and then rose to about 9 feet below site grade. The site is located in a rural setting, surrounded by agricultural land. Groundwater is kept at a depth of about 9 feet below grade by a drainage system that is maintained and operated by the local drainage district. A letter was written by the district board president and provided to the RA stating that groundwater would be kept below a depth of 9 feet at the school in perpetuity.

CONCLUSIONS

Soft clay deposits can exhibit settlement due to cyclic softening during strong earthquake shaking. The potential for cyclic softening should be evaluated in conjunction with a liquefaction analysis to provide a complete assessment of potential seismic settlement. As described above, less than one half inch was added to the total seismic settlement estimate for a public school site investigation due to cyclic softening induced settlement. This project made apparent the need for developing and refining procedures for estimating settlements induced by liquefaction and cyclic softening.

It became very clear throughout this process of regulatory agency approval that good communication is the key to getting a project approved. Written responses to agency comments, without first making verbal contact can leave some misunderstood comments left unanswered and result in multiple iterations of comments and responses without resolution.

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