Liquefaction susceptibility of soft alluvial silts in the Willamette Valley

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ABSTRACT

The Tualatin and Portland basins of the Willamette Valley contain vast deposits of very soft to very loose alluvial silts. Large sections of Portland, Hillsboro, Beaverton, and Forest Grove have numerous structures and civil works situated on these flood-plain deposits. Due to the recent upgrading of potential seismic ground motions in western Oregon, the question arises: "Can these saturated silt deposits liquefy?" The behavior of sands and silty sands to earthquake shaking is well understood, and there are widely used, simple empirical charts to evaluate the liquefaction potential for sands, using standard penetration test (SPT) blowcount data. There is not, however, a similar comprehensive knowledge of the seismic behavior of predominantly silty material.

This paper describes the results of cyclic triaxial laboratory tests performed on relatively undisturbed samples of nonplastic, alluvial and flood-deposit silts from a site in the Tualatin basin near Forest Grove in Washington County. Five specimens were tested under various cyclic stress ratios to evaluate the response of the silt to cyclic motions. The test results indicated that all specimens developed a state of initial liquefaction and that four of the five specimens "liquefied," i.e., developed excess pore-water pressures equal to the initial effective confining stress, under cyclic stress ratios and number of uniform cycles representative of postulated earthquakes from crustal and subduction sources.

The results of this study clearly indicate that nonplastic alluvial silts can liquefy under design-level earthquakes. However, the results are site specific, and one must exercise care and judgment before using these results at other sites throughout the Willamette Valley. For example, the effects of increasing plasticity, which is common in many alluvial deposits in the valley, has not been addressed. Much research is needed before the overall seismic behavior of these alluvial materials is fully understood.

INTRODUCTION

The Fern Hill Water Treatment Plant is located about 2 mi south of Forest Grove on the Tualatin River flood plain (Figure 1). The plant is currently being expanded to accommodate increased water-supply needs for several Washington County communities, including Hillsboro and Forest Grove. Current geotechnical studies for the expansion project included a review of existing geotechnical reports from the original plant construction in 1974, the drilling of several borings to evaluate subsurface conditions for specific foundation locations, and a site-specific seismic hazard evaluation.

According to the previous geotechnical information and current borings, the subsurface material at the site consists of 80–85 ft of fine-grained deposits, which are predominantly silts originating from Quaternary catastrophic flood deposits and alluvium. The upper 30–50 ft of this deposit consists of very loose to medium-dense silt, with Standard Penetration Test (SPT) blowcounts[1] ranging from 2 to 21 blows per foot (bpf), with an average blowcount of 8.5 bpf. Groundwater is typically within 5–10 ft of the ground surface. Classification tests indicated that the material is essentially nonplastic. Due to the low blowcounts and low plasticity, the design team became concerned that these silts were potentially liquefiable under current design-level earthquakes. A representative boring log is shown in Figure 2.

[1] Standard penetration test blowcount is the number of blows (of a 140-lb hammer falling freely through a height of 30 in.) to drive a standard sampling tube 12 in. into the ground.

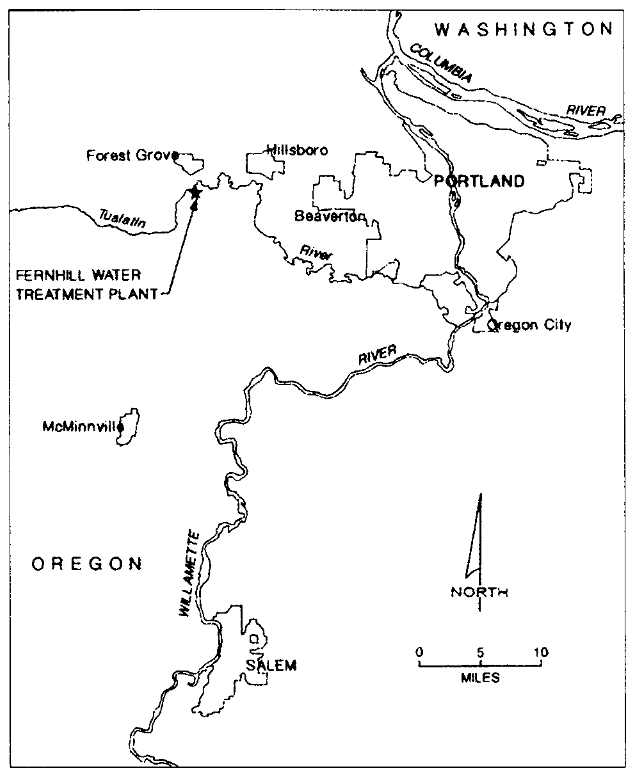


Figure 1. Sketch map showing location of the Fernhill water treatment plant, the site discussed in this paper.

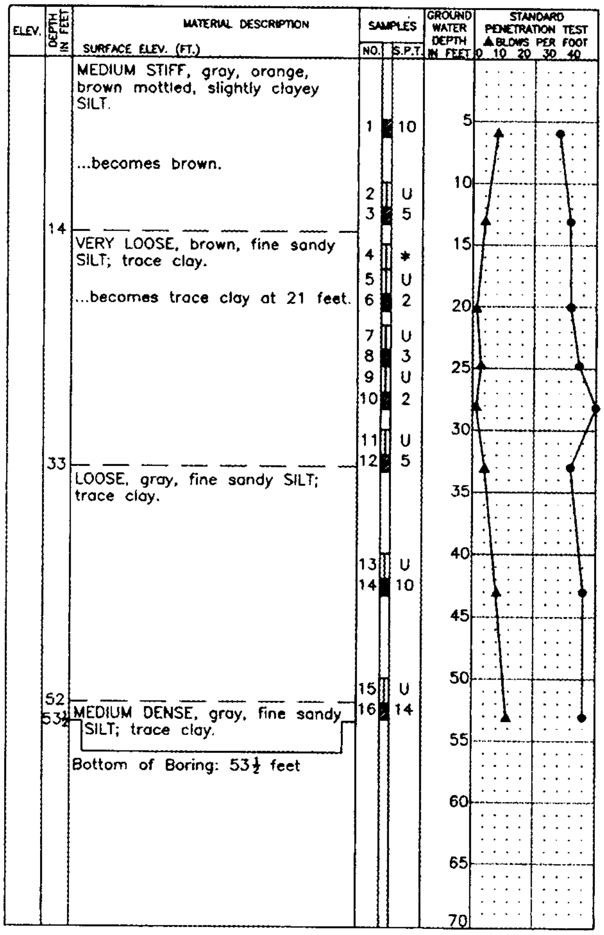


Figure 2. Representative boring log. U *=Shelby tube sample; * = no sample recovered; curve on extreme right marked by circles shows moisture content in percent.*

DESIGN GROUND MOTION

Representative ground motions were developed for several potential seismic sources including crustal earthquakes and intraplate and interface subduction earthquakes. The ground-motion parameters were developed from a comprehensive seismic hazard evaluation performed for the Barney Reservoir expansion project located 15 mi west of the site (Cornforth Consultants, 1994). That study assessed bedrock motions on a probabilistic and deterministic basis and developed synthetic acceleration-time histories for each source.

For the Fern Hill site, the peak rock-acceleration values from Barney Reservoir were attenuated by averaging several empirical relationships for crustal earthquakes (Joyner and Boore, 1982; Idriss, 1991; and Sadigh and others, 1993) and by using relationships developed by Youngs and others (1988) for the subduction earthquakes. Synthetic time histories were scaled to match the attenuated peak ground acceleration. The deterministic ground motions used at the site are presented in Table 1.

Table 1. Deterministic ground motion (bedrock)

Source	Maximum credible earthquake (MCE)	Minimum distance (mi)	Peak bedrock acceleration mean (*g*)
Portland Hills fault zone	6.8	16	0.16
Intraslab	7.3	30	0.22
Interface	8.5	40-55	0.14

The seismic response of the alluvial soils overlying the bedrock was calculated by use of the program SHAKE91 (Idriss and Sun, 1992). A generalized stratigraphy of the site was developed from the boring logs. Representative shear-wave velocity data for similar soil types were obtained from a review of geophysical testing by DOGAMI on 30 drill sites in the Portland basin (Mabey and Madin, 1995). The results of the dynamic analysis indicate that cyclic stress ratios induced by the earthquakes $(CSR)_{eq}$ would range from 0.18 to 0.29 from the ground surface to a depth of 45 ft.

PRELIMINARY LIQUEFACTION EVALUATION

As a first step in evaluating the susceptibility of the silts to seismic ground motions, the factor of safety against initial liquefaction (FS_l) was calculated in a simplified empirical procedure using SPT blowcount data (N) corrected for overburden pressure, earthquake magnitude, and hammer efficiency (Seed and others, 1983). For corrected SPT blowcounts—expressed as $(N_1)_{60}$—in the range of 4–11, the empirical data for silty sands indicate that cyclic shear stress ratios of 0.12–0.23 must be induced in the ground to cause liquefaction.

Comparing the cyclic stresses induced by the earthquakes with the cyclic shear strength from the empirical chart indicated that the loose deposits of the silt in the upper 50 ft would be susceptible to earthquake-induced liquefaction. However, the design team questioned the validity of the results, since they were obtained from a procedure that was originally developed for sands and silty sands, not for fine-grained silts. Do silts exhibit similar seismic behavior as sands? It was decided to test undisturbed samples of the silt in a cyclic triaxial test apparatus to evaluate the response under simulated earthquake loading.

SOIL CLASSIFICATION PROPERTIES

Three relatively undisturbed (Shelby tube) samples were obtained from the site from depths between 21.5 and 32 ft. Several classification tests were performed on these samples, including natural water content, grain size distribution, and Atterberg limits. Grain size analyses were performed for all five test specimens. On average, the specimens contained 15 percent fine sand, 83 percent silt fraction, and 2 percent clay (Figure 3). The plasticity index (PI) for the five specimens ranged from 0 to 3, with an average of 1.6, which is essentially nonplastic. SPT blowcounts obtained immediately below each tube sample were 3, 2, and 5,

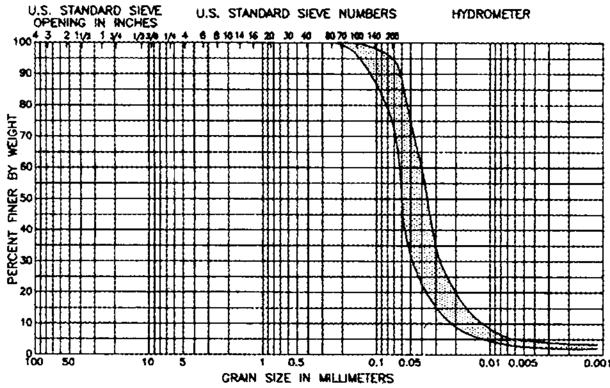


Figure 3. Range of particle size for 5 cyclic triaxial specimens.

respectively, and the corrected average blowcount SPT $(N_1)_{60}$ was 4. Natural water content ranged from 35 to 55 percent and was fairly uniform in the upper 50 ft.

SAMPLE TRANSPORTATION

Cyclic triaxial testing was performed at the Geotechnical Laboratory at the University of California at Berkeley. To help minimize sample disturbance prior to transporting the samples to Berkeley, the end caps of the tubes were removed, and the tubes were left on end with moist filter cloth to allow the sample to drain excess water, thereby mobilizing capillary tension within the sample. As a further precaution, the tube samples were carefully packaged, then hand-carried on a commercial flight to Oakland, California.

SPECIMEN PREPARATION

Triaxial specimens (nominally 2.8 in. in diameter and 6 in. in height) were extruded from segments of the Shelby tubes with a modified hydraulic jack. Capillary stresses in the partially saturated silts were sufficient to maintain free-standing specimens after extrusion. Following placement of the top cap and the latex membrane, each specimen was vacuum saturated and measured, and the triaxial cell was assembled around it. An effective confining stress of approximately half an atmosphere (1,000 pounds per square foot [psf]) was maintained throughout the vacuum and back-pressure saturation processes. The specimens were then consolidated to an isotropic stress of 1,500 psf prior to undrained cyclic loading. Volume changes during both the saturation and consolidation phases were closely monitored and were observed to be small, which satisfied the intent of reconsolidating relatively undisturbed specimens.

CYCLIC TRIAXIAL TESTING

The triaxial tests were performed by use of the CKC e/p pneumatic loader, under the control of Georobot software (version 5.2). Instrumentation included an externally mounted, 500-pound-capacity load cell, a 1.00-in. Collins LVDT, and three differential pressure transducers of varying sensitivities. All of the instrumentation and other components of the systems were calibrated prior to testing.

The cyclic testing consisted of uniform, stress-controlled, sinusoidal loading under undrained conditions at a frequency of 1 cycle/second. The cyclic stress ratios (CSRs), which are a measure of the amplitude of loading, were chosen to span the range expected to result from the design seismic events at the project site. Throughout this report, the cyclic stress ratio is defined as the peak cyclic deviatoric stress (σ_{dc}) divided by two times the initial effective consolidation stress (σ'_{con}):

$$CSR = \frac{\sigma_{dc}}{2\sigma'_{con}}$$

Cyclic loading was applied to all of the isotropically consolidated specimens until they had reached axial strains in excess of 8 percent. In all cases, this occurred after the specimens reached a state of initial liquefaction (at which the effective confining pressure, 3, first reaches a value of zero).

RESULTS OF TESTING

The data from the five cyclic tests are summarized in Table 2. Initial conditions for each specimen include the original depth and the dry density (γ_d) immediately prior to cyclic testing. The results of each test are described by the cyclic stress ratio (CSR), and the number of cycles required to reach "initial liquefaction," defined as the achievement of a pore pressure ratio of $r_u = \Delta u/\sigma'_{con} = 100\%$, where Δu is the change in pore-water pressure.

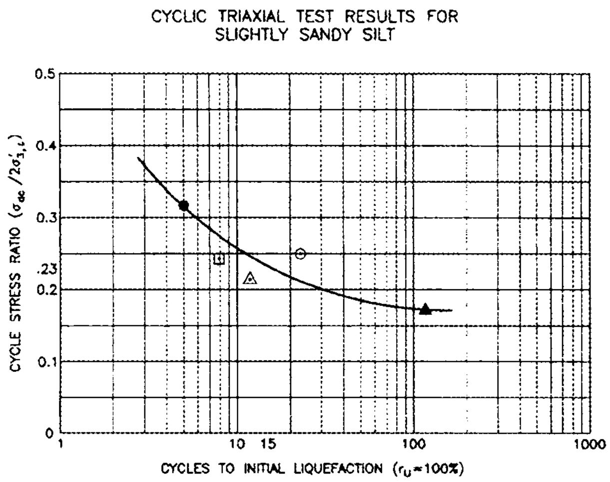
Table 2. *Results of cyclic triaxial testing of Willamette silts*

Test	Sample depth (ft)	Blow-count $(N_1)_{60}$	In situ dry density, γ_d (pcf)	Cyclic loading (CSR)	Number of cycles ($r_u = 100\%$)
7T	22	4	81.7	0.250	22
7M	22.5	4	80.9	0.327	5
7B	23	4	79.3	0.220	12
9T	26	3	82.5	0.177	105
11T	31	5	83.2	0.247	8

As has been frequently observed in cohesionless soils, the onset of substantial cyclic straining (greater than 5-percent axial strain) roughly coincided with initial liquefaction. The values of CSR versus the number of cycles to initial liquefaction are plotted for the five tests in Figure 4.

CONCLUSIONS

The laboratory testing performed on the samples of alluvial silt during the current study generally confirmed the results of the simplified empirical procedure based on SPT blowcount data. Despite the low percentage of sand-sized particles, these materials are prone to liquefaction when subjected to moderate cyclic loading. Due to the lack of co-



TEST NO.	SYMBOL	SAMPLE DEPTH (FT)
CC-4, 7T	⊙	22
CC-4, 7M	●	22½
CC-4, 7B	△	23
CC-4, 9T	▲	26
CC-4, 11T	⊡	31

INITIAL EFFECTIVE CONFINING STRESS, ($\sigma'_{3,i}$) = 1,500 psf

Figure 4. Cycles to initial liquefaction for slightly sandy silt.

hesive fines in the material, and low SPT values indicating a very loose structure, it is likely that the samples retrieved from the field were at least slightly disturbed during the sampling process. This disturbance would be expected to densify the material and, as a result, increase the liquefaction resistance of the specimens tested in the lab; therefore, the data plotted in Figure 4 are suspected of representing levels of liquefaction resistance that are greater than those available in equivalent deposits in situ.

In light of the difficulties in evaluating the degree of disturbance and the magnitude of its possible effects, it seems unreasonable to attempt to quantify them and subsequently "correct" for these effects. The cyclic and static test results can probably best be considered as "upper bound" values on the liquefaction resistance and post-liquefaction strengths, respectively, of the rather low-density silt deposit from which the specimens were obtained.

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Wang to head DOGAMI earthquake hazard reduction efforts

Yumei (Mei Mei) Wang has been appointed to lead the earthquake hazard activities for the Oregon Department of Geology and Mineral Industries (DOGAMI).

Wang, an earthquake engineer with DOGAMI since 1994, will lead a team of geologists and scientists who specialize in studying earthquake hazards in Oregon. She will also work with local, state, and national earthquake groups in forming partnerships for mitigation efforts to reduce loss of life and property.

Wang recently authored the earthquake hazard maps for the Salem area (DOGAMI Geological Map Series GMS-105, 1996). She and other scientists are now working on similar maps for the Eugene-Springfield area.

The hazard maps are part of a larger project to protect Oregonians from earthquake damage. Through Wang and other earthquake professionals, DOGAMI is increasing its efforts to promote earthquake awareness and preparedness.

Wang earned her master's degree in civil engineering with a geotechnical emphasis from the University of California at Berkeley in 1988. Before coming to DOGAMI, she had her own geotechnical engineering consulting firm in Oakland, California. She is an officer for the American Society of Civil Engineers and a member of the Earthquake Engineering Research Institute, the Association of Women Geoscientists, and the Association of Engineering Geologists (AEG). She is chairperson for the AEG's 1997 earthquake symposium.

Wang replaces Matthew Mabey, who left DOGAMI this summer to accept a teaching position at Brigham Young University. □