HIDDEN HAZARD: LIQUEFACTION ASSESSMENT FOR A BURIED GLACIAL STREAM VALLEY

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ABSTRACT

A RCRA- compliant On-site Containment Facility (OCF) is proposed at the former Asarco Smelter Superfund (CERCLA) Site along the shore of Commencement Bay at Tacoma, Washington. The smelter occupied a slag platform that extends more than 200 m offshore and is 15 m thick at the outboard edge. As originally planned, the OCF was to be built on the slag platform. During the site investigation, it was discovered that the proposed OCF site straddled a buried alluvial valley formed by erosion to lower sea levels during the Pleistocene ice ages. When sea level rose to its present level, the mouth of the ancient stream was filled with loose lagoon deposits and covered by recent marine shoreline deposits. This complex geological environment was then obscured by slag, creating a geological hazard with no surface expression. This paper presents the field programs used to investigate the site conditions and analyses performed to assess liquefaction in the loose alluvial silts and sands, and marine sands.

INTRODUCTION

The former Asarco Tacoma Smelter Site is located along the shore of Commencement Bay in the municipalities of Ruston and Tacoma, Washington (Figure 1). The smelter produced metals from 1890 until 1986. Following closure, the site was included in the Commencement Bay Nearshore Tideflats Superfund Site, and was the subject of a Remedial Investigation (RI) and Feasibility Study (FS) conducted by Asarco. In 1995, the U.S. Environmental Protection Agency (EPA) issued a Record of Decision (ROD), describing a Selected Remedy which is the basis for future remedial work.

A critical component of the Selected Remedy is a Resource Conservation and Recovery Act (RCRA)–compliant On-site Containment Facility (OCF), that meets RCRA/CERCLA requirements for landfills. The OCF will contain about 198,600 m^3 of contaminated soils, fill, and demolition debris. Site selection was driven by planned post-remediation development of the slag platform for public use. As shown on Figure 1, the OCF as proposed

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in 1995 was to be a circular facility with a ring road and a lighthouse atop the center of the reclamation cover.

SITE CONDITIONS AND GEOLOGY

Topography and Surface Features

Steep, northwest-southeast trending bluffs parallel the shoreline. Bluff elevations range from about 27 to 61 m above mean sea level (MSL). A large portion of the Smelter Site is situated on an artificial terrace constructed from fill and slag which extends about 210 to 240 m from the original shoreline into Commencement Bay at an elevation of about 3 m MSL (Figure 1).

Small streams have incised through the bluffs to form relatively steep, narrow drainages. The Cooling Pond drainage crosses the site at the proposed OCF location (Figure 1). Within the Smelter Site proper, the stream channels are obscured by fill and slag. Storm runoff discharges to Commencement Bay through buried storm drains.

Geology

The geology in the vicinity of the Smelter Site is predominantly the result of repeated continental glaciation. About 14,000 years ago, the last glaciers retreated from the Tacoma area, exposing the topographic low presently occupied by Commencement Bay. As the ice retreated, sea level gradually rose. The rising water level eventually submerged the stream drainages which had incised into the glacial material when sea level was much lower. Lagoons formed at the stream mouths, and mixtures of silty and sandy stream alluvium, peat, and fine-grained materials were deposited. As sea level continued to rise, marine sand and gravel (beach deposits) covered the alluvial and lagoon material in the stream channels. About 5,000 years ago, sea level stabilized near its present level. The modern slag platform created a hard cap over this complex subsurface assemblage.

Seismicity

Large historic earthquakes in the Puget Sound region appear to have relatively deep focal depths, suggesting that they are related to the inferred sinking (subducting) Juan de Fuca oceanic slab beneath Puget Sound (Crosson and Noson, 1979; Gower et al., 1985). The largest earthquake recorded in this area was the 1949 magnitude 7.1 Olympia earthquake approximately 27 km southwest of the Smelter Site. The focus of this earthquake was at a depth of 54 km. The second largest earthquake recorded was the 1965 magnitude 6.5 Tacoma earthquake approximately 19 km northeast of the Smelter Site at a focal depth of about 60 km (Noson et al., 1988).

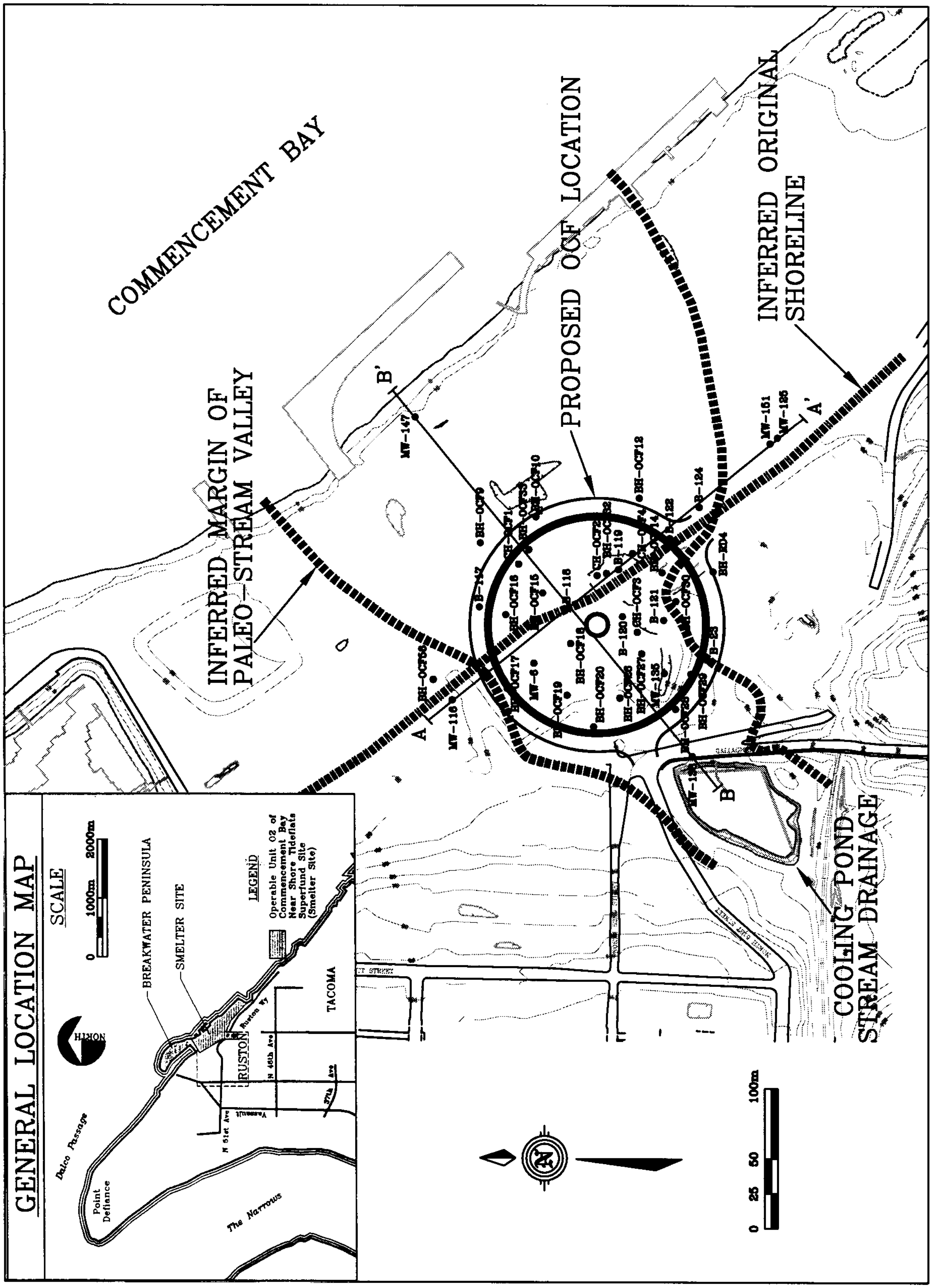

FIG. 1. Proposed OCF Site Location Map

Site specific deterministic and probabilistic seismic hazard evaluations were prepared (Abrahamson, 1995 and 1997). For the probabilistic evaluation (ground motion with a 90 percent chance of not being exceeded in 250 years), the peak ground acceleration (PGA) is 0.35g, normalized to a magnitude 7.5 earthquake on the Benioff (subduction) zone. For the deterministic evaluation, the PGA is 0.49g for a magnitude 7.5 earthquake (84th percentile ground motion).

Subsoil Conditions

Figure 1 illustrates the location of the buried paleo-stream drainage and beach/shoreline area. Stream valley and shoreline locations are defined from subsurface data collected for this investigation, and from a map of the Smelter Site dating back to about 1896. The relative positions of the former stream drainage and shoreline with respect to the proposed OCF location are important because these geomorphic features control the distribution of potentially liquefiable soils.

Geologic cross- sections through the proposed OCF location are presented on Figures 2, 3, and 4. Cross section A-A’ (Figure 2) is a transverse section of the paleo-stream valley located along the edge of the former beach area. Cross section B-B’ (Figure 3) is a longitudinal profile through the stream channel perpendicular to the Commencement Bay shoreline. Figure 4 is a detailed presentation of a portion of cross-section B-B’.

Slag underlies much of the plant site, and is in turn underlain by marine sand/gravel and alluvial/lagoon deposits. The slag ranges in thickness from about 0.3 m along its western margin to approximately 15 m at the present shoreline. The distribution of the slag is shown in Figure 3. The slag was deposited as molten or near-molten material and has a lava-like appearance at ground surface. However, the hot slag often shattered when it came into contact with the sea water, and is typically gravel-like below about 1.5 to 3 m depth.

A layer of wood and fill, including sawdust, wood chips, and logs, often occurs at the base of the slag. The wood debris is remnant from a former lumber mill operation at the site.

Figure 2 illustrates the lateral extent of the paleo-stream valley in the Cooling Pond area and the distribution of alluvium beneath the fill and marine deposits. The alluvium is up to 8 m thick in the center of the drainage. The alluvial deposits extend seaward beyond the edge of the slag terrace, having been deposited in a stream channel cut to a former, lower sea level.

The alluvium varies from relatively clean sand to silty clay with scattered gravel. Typically it consists of loose sandy silt to silty sand with gravel and abundant organic debris and wood fragments. At the distal portion of the drainage, where the stream formerly discharged into Commencement Bay, the alluvium contains peat and abundant shell fragments, indicating a marsh/lagoon environment (Figure 4).

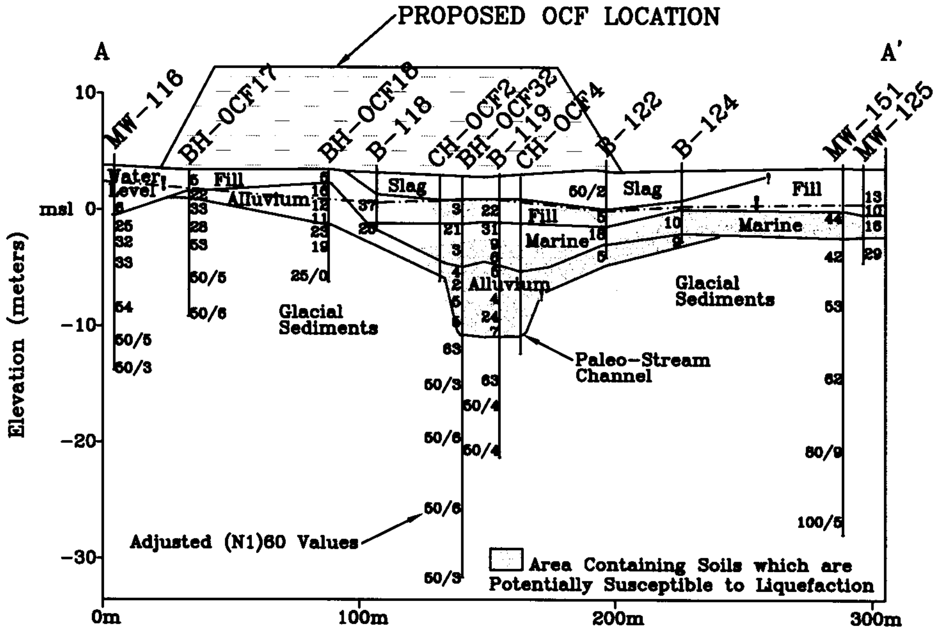

FIG. 2. Cooling Pond Drainage Perpendicular Profile (Cross Section A–A')

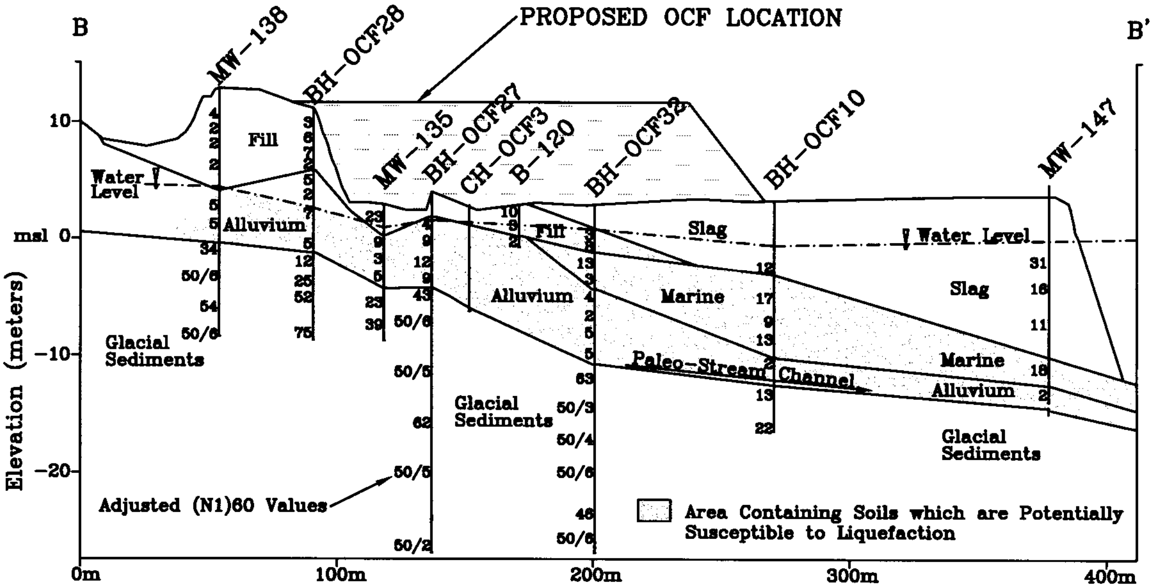

FIG. 3. Cooling Pond Drainage Longitudinal Profile (Cross Section B–B')

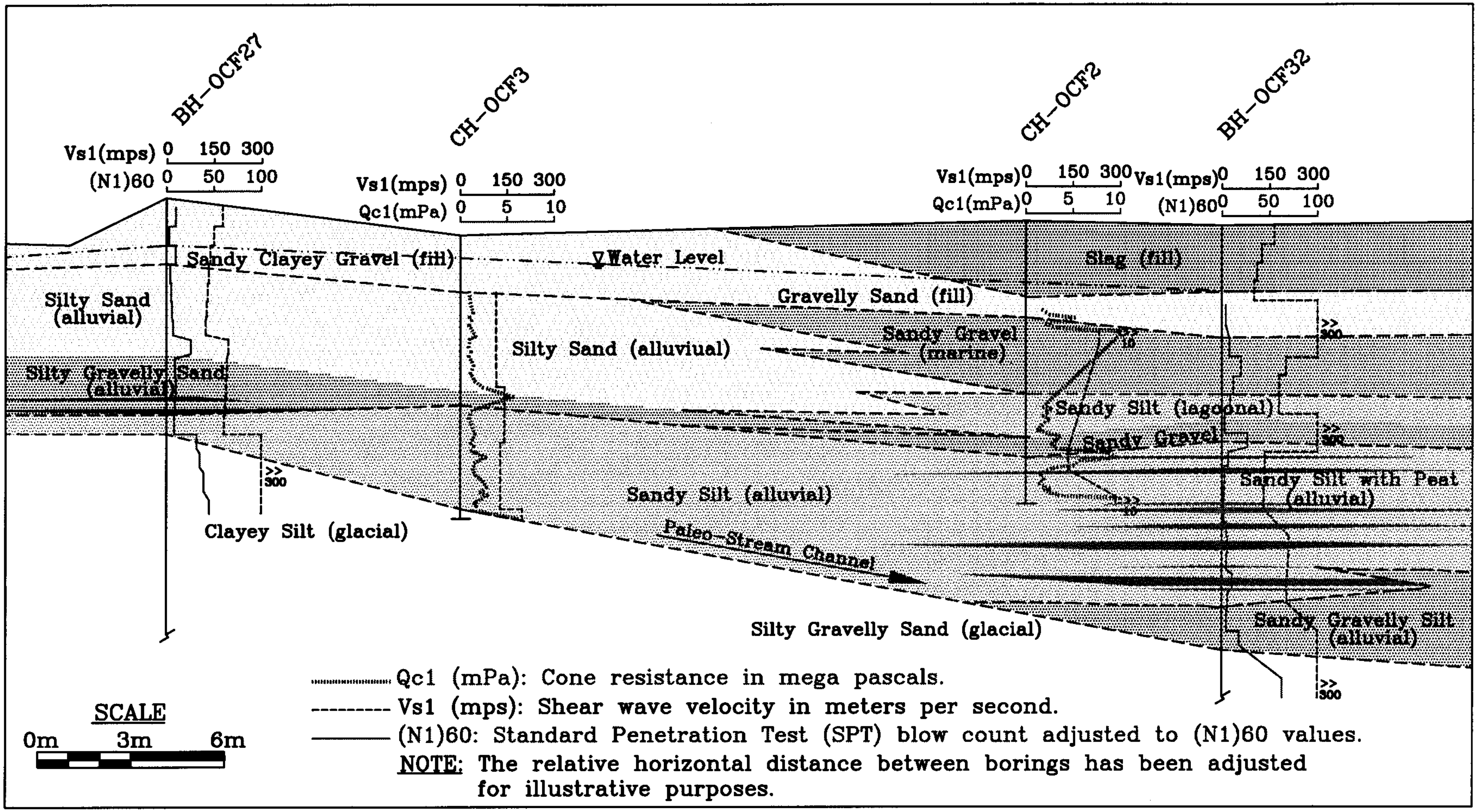

FIG. 4. Longitudinal Cross Section of the Cooling Pond Drainage

The marine beach deposits are generally cleaner and more uniform than the alluvium, typically consisting of slightly silty fine- to medium-grained sand with abundant 12 mm to 50 mm, subrounded gravel, often containing shell fragments. The thickness of the marine sediments ranges from less than 0.3 m near the original shoreline to about 6 m near the center of the pale-stream valley.

The underlying glacial drift includes till, outwash sand and gravel, and lacustrine (lake beds) silt and clay with interbedded sand and gravel.

Groundwater levels in the vicinity of the proposed OCF location are depicted on Figures 2, 3, and 4. Water levels range in depth from about 1.5 m to 4.5 m, controlled by tides.

SITE CHARACTERIZATION INVESTIGATION METHODS

Drilling and in-situ testing methods followed procedures consistent with local and standard practice (Seattle Section ASCE and University of Washington, 1995; Youd and Bennett, 1983; and Seed et al., 1984).

Drilling Methods

The site was difficult to explore due to the extreme contrast between the rock-like slag and the loose/soft alluvium. Test borings were drilled with hollow stem augers where possible. In areas overlain by slag, the ODEX (overburden drilling with eccentric bit) method was used to penetrate the slag, and mud rotary drilling techniques were used below the slag. ODEX allowed rapid penetration of the slag and provided a casing through which to drill and sample underlying beach and alluvial deposits. Selected borings were completed with solid 76 mm schedule 40 PVC casing for downhole shear wave testing.

Sampling Methods

Two sampling methods were used, depending upon material types. In soft ground, the standard penetration test (SPT) was used, driven by a 63.5 kg (140 pound) above ground safety hammer on a Mobile wireline with a manual release. AW rods were used above 15 m depth and NW rods were used below 15 m (Seed et al., 1984). Other procedures were consistent with ASTM D 1586.

In harder ground, a larger split-barrel sampler (76 mm [3.0 in] OD, 61 mm [2.4 in] shoe diameter) was used, driven by a 136 kg (300 pound) above ground safety hammer. The sampler and hammer were connected to a NW rod.

Energy transferred to the drill rods was measured by Goble Rausche Likins and Associates, on a section of the drill rod several feet below the hammer. A Pile Driving Analyzer (PDA) processed acceleration and strain measurements from each hammer blow, as specified by ASTM D 4945. Energy transfer past the gage was computed using force and velocity records

(Abou-matar and Goble, 1997). Average computed efficiencies were 66 percent for the 63.5 kg hammer and 75 percent for the 136 kg hammer.

The field N-values were adjusted to $(N_1)_{60}$ using procedures presented by Seed, et al. (1984). The $(N_1)_{60}$ values were adjusted for short drill rods, overburden pressure, hammer efficiencies, hammer and sampler size (Fang, 1991), and sampler liner correction factor (when liners were not inserted). Adjusted $(N_1)_{60}$ values for OCF borings BH-10, BH-27, and BH-32 are presented on the cross-sections of Figures 2, 3, and 4.

Cone Penetration Tests

Cone penetration tests (CPT) were performed by Hughes Insitu Engineering at four sites (CH - OCF 1, 2, 3, and 4). Coarse fragments in the slag and fill stopped the cones, requiring penetration using ODEX. Electric cones were pushed by the drill rig below the casing. Cone penetration results were normalized for overburden pressure using a cone resistance factor proposed by Seed, et al (1983). The corrected tip resistance (q_C1) is normalized to a reference stress equal to about one atmosphere (100 kPa). The corrected CPT values (CH-2 and 3) used in liquefaction analyses are presented in Figure 4.

Shear Wave Velocity Tests

Downhole shear wave tests were performed by Redpath Geophysics. Holes OCF 27, 32, and 33 were cased to depths of 30 m or more using solid 76mm schedule 40 PVC. Cement-bentonite grout was injected into the annulus through a valve in the end cap of each casing at least one week prior to testing. The casings were filled with water when completed to prevent floating, and the water was pumped out prior to testing to reduce “tube wave” effects (i.e., creation of seismic “noise” by transmittal of waves along the casing). Shear waves were generated by striking the ends of a plank secured under the wheels of a vehicle.

Shear wave velocities were also recorded by Hughes Insitu Engineering during the cone penetration tests. The cone assembly contains a geophone, and shear wave velocities were recorded at about 2-foot intervals. Shear waves were generated by striking the ends of a plank placed beneath the rear jacks of the drill rig. The seismic cone is a form of the downhole test.

Shear wave velocities were normalized for overburden pressure using a correction factor proposed by Robertson, et al. (1992). The corrected velocity (V_S1) is normalized to a reference stress equal to about one atmosphere (100 kPa). The results are presented in Figure 4.

LIQUEFACTION EVALUATION

Factors of safety against liquefaction (FS_L) were calculated using normalized data from standard penetration tests ($(N_1)_{60}$), cone penetration tests (q_C1), and shear wave velocities (V_S1). Existing stress conditions (i.e., without the OCF in place) were assumed in the calculations.

The calculations take on a similar form for each type of data. Using a normalized PGA of 0.35g, equivalent cyclic stress ratios (CSR)eq are computed, which are a function of depth, maximum acceleration, and overburden stress. Values of SPT, CPT, and V_S are used to estimate the equivalent cyclic stress ratio required for liquefaction $(CSR)_l$. The factor of safety is determined by dividing $(CSR)_l$ by (CSR)eq.

Based on SPT Data

FS_L was calculated from SPT results using empirical methods suggested by Seed and Idriss (1982) and Seed and Harder (1990): The unadjusted equivalent uniform cyclic stress ratio required to trigger liquefaction $(CSR)_l$ was estimated for values of $(N_1)_{60}$ for sands and silty sands using a chart from Seed, et al (1984). $(CSR)_l$ values for silts and gravels were estimated using charts from Stark and Olson (1995). The adjusted equivalent uniform cyclic stress ratio $(CSR)_{l,field}$ necessary to cause liquefaction was calculated using

$$(CSR)_{l,field} = (CSR)_l C_M K_\sigma K_\alpha \text{ (Seed and Harder, 1990).}$$

where C_M is a correction for an earthquake larger or smaller than magnitude 7.5. In this case, $C_M = 1$, K_σ is a correction for effective vertical stress, and K_α is a correction for slope (one for this case).

Based on CPT Data

Appropriate values for the equivalent cyclic stress ratio (CSR)eq are as previously described. The factors of safety against liquefaction were then calculated as follows:

The equivalent uniform cyclic stress ratio $(CSR)_l$ required to trigger liquefaction was estimated for values of q_C1 using charts from Stark and Olson (1995).

The equivalent uniform cyclic stress ratio $(CSR)_{l,field}$ necessary to cause liquefaction and the factors of safety were calculated using an identical procedure to that described for the SPT.

Based on Shear Wave Velocity Data

Shear wave velocities were analyzed as follows.

The equivalent uniform cyclic stress ratio $(CSR)_l$ required to trigger liquefaction was estimated for values of Vs1 using a chart from Robertson, et al (1992).

The equivalent uniform cyclic stress ratio $(CSR)_{l,field}$ necessary to cause liquefaction and the factors of safety were calculated using an identical procedure to that described for the SPT.

Factors of Safety Against Liquefaction (FS_L)

The calculated factors of safety (FS_L) are in the range 0.2 to 1.0 for many of the sands, silty sands, sandy gravels and sandy silts, strongly suggesting the site is liquefaction-prone. These results are summarized in Table 1 for three borings along OCF Cross Section B-B' using SPT, CPT, and shear wave velocity data. Results of the three methods were very similar.

Lateral Spreading

The very low factors of safety against liquefaction (FS_L) indicate that slope spreading may occur. Slope stability analyses were performed assuming failure along the liquefiable layers, using residual undrained shear strength values estimated from $(N_1)_{60}$ values adjusted for estimated fines content (Seed and Harder, 1990). Factors of safety against lateral spreading are very low (less than 0.4). Therefore, it appears that lateral spreading is likely in the event of major seismic ground motion. The slag appears at surface to be a more-or-less monolithic slab. However, it is known to be highly broken below the water table, and it was assumed that the slag would break up and behave as a granular soil.

Liquefaction Settlement

Settlement due to liquefaction was estimated using the relationship between $(N_1)_{60}$ and volumetric strain for saturated clean sands developed by Tokimatsu and Seed (1987). The $(N_1)_{60}$ values were adjusted for fines content using values suggested by Seed and Harder (1990). Some soils at the site contain significant silt contents, requiring the calculated $(N_1)_{60}$ values to be adjusted upward by 1 to 5 blows/foot. The worst case for liquefaction settlement was calculated at borehole OCF32, where about 10 inches of liquefaction settlement is predicted.

CONCLUSIONS

Based on the results of field and laboratory grain-size tests and analyses cited in this paper, the following conclusions and recommendations can be made:

- Geomorphologic assessment and review of historical records/maps are very useful in evaluating subsurface conditions along the coastal area in the Puget Sound Region. Investigators must understand the geological/glacial history. Sea level fluctuations
- Hammer energy should be measured for the specific drill rig, procedures, and sampling equipment used on important projects.
- The three methods (SPT, CPT, and shear wave velocity) consistently predict liquefaction in the same layers.
- It is very important to have stratigraphic data, as obtained from the SPT. Variances in soil texture that affect liquefaction may not be detectable using CPT or V_S. In particular, cone and velocity data alone may tend to predict liquefaction in layers that are too fine or clayey to liquefy.
- The larger split barrel sampler driven by the in gravels produced very similar$(N_1)_{60}$ values to the SPT, when adjusted using relationships suggested by Fang (1991).
- Based on the results of this investigation and preliminary ground improvement cost analyses, the OCF site was moved to an area where the foundation souls are predominantly overridden glacial deposits.

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