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Technical Note

Unsaturation Beneath a Water Table

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INTRODUCTION

The water table is a fundamental concept in hydrogeology. In standard hydrologic and geotechnical practice, it is the elevation to which water will fill a hole if the borehole is drilled into the top of the shallowest water-bearing zone. As Hubbert (1940) has shown, this definition of the water table corresponds to a surface on which fluid pressure is atmospheric, which is a definition that implies nothing about saturation. Many textbooks take note of this but also point out that a zone above a water table may be saturated with water at sub-atmospheric pressure because of capillarity (e.g., Davis and DeWiest, 1966; Freeze and Cherry, 1979; and Selker et al., 1999). The potential for unsaturation beneath a water table, however, is seldom acknowledged, except for perched conditions. For example, the American Geological Institute's *Glossary of Geology* defines the water table as "the surface between the *saturated zone* and *unsaturated zone*; that surface of a body of *unconfined groundwater* at which the pressure is equal to that of the atmosphere," which implies they are equivalent (Jackson, 1997). In addition, some textbooks have defined the water table as the top of the zone of saturation (e.g., Walton, 1970; Fetter, 1988; and Domenico and Schwartz, 1997), although it should be noted that the definition is corrected in Fetter's fourth edition (Fetter, 2001). The purpose of this paper is to describe a field example that documents the presence of unsaturation beneath a water table under naturally occurring conditions.

The primary significance of documenting unsaturation beneath a water table, apart from confirming the need for care in defining the water table, is to indicate the need for caution in the use of seismic refraction surveys to determine depths to water tables. In addition, recognition of the possibility of unsaturation beneath the water table has potential application to the spectral-analysis-of-surface-waves method (used to determine vertical profiles of shear [S]-wave velocity) for which Poisson's ratio is usually assumed to be constant beneath the water table (e.g., Brown et al., 2002). This assumption implies a constant ratio of the velocities of S and compressional (P) waves. Finally, the observation may be relevant to the prediction of peak vertical ground acceleration, which is sensitive to local P-wave velocity (e.g., Mueller et al., 1982).

In this investigation, the authors rely on the seismic velocity of P waves to indicate saturation. Both theoretical considerations and experimental investigations indicate that P-wave velocity is very sensitive to soil saturation (Biot, 1956; Allen et al., 1980). A reduction of only 0.2 percent from saturation can reduce the velocity of P waves by half (Allen et al., 1980). Despite the sensitivity of P waves to saturation, field descriptions of the effect of unsaturation on seismic-wave propagation are rare in the groundwater literature. The only other published field report of which the authors are aware is that of Bonnet and Meyer (1988), who compared water tables measured in borings beneath a vineyard under irrigation with the water table as inferred by seismic refraction. They concluded that an unsaturated zone was present beneath the water table as measured in the shallow borings. This unsaturation beneath the water table should not be confused, however, with unsaturation beneath a perched groundwater system, which is commonly described in the literature (e.g., Catchings et al., 2002).

The data presented here were collected from 1985 to 1989 as part of an investigation to find and instrument a site at which to monitor earthquake-induced liquefaction (Holzer et al., 1988) that would be caused by the predicted and highly anticipated Parkfield, California, earthquake (Bakun and Lindh, 1985). The nature of the data collection reflects that purpose. First, it was necessary to find a site with a shallow water table and more than 5 m of saturated Holocene sediment. To identify potential sites, a regional reconnaissance with simple seismic refraction surveys was conducted in anticipation that the velocity contrast between Holocene and Pleistocene sediment would be sufficient to permit

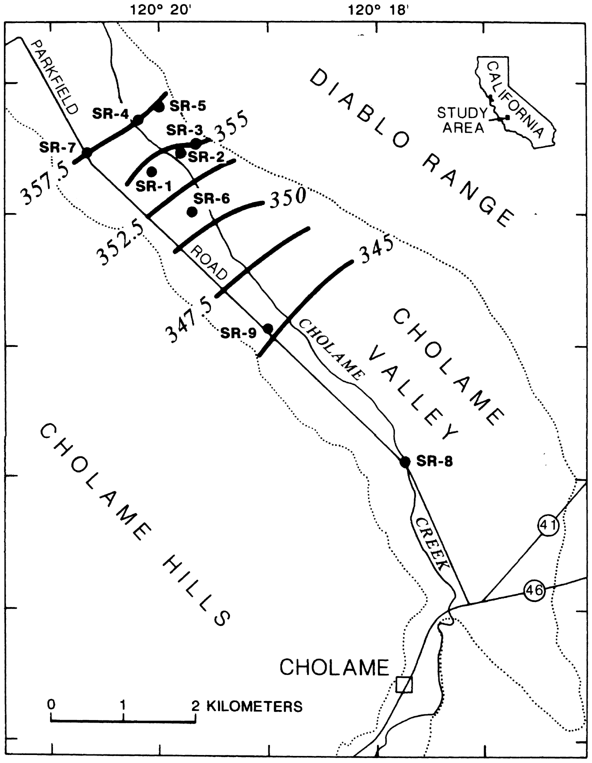

Figure 1. Map of Cholame Valley, California, with locations of seismic refraction surveys and water-table elevation in meters. Water table was measured on June 5–7, 1985.

estimation of the thickness of the Holocene sediment. Boreholes were simultaneously hand-augered at each survey site to determine depths to the water table. After the reconnaissance, cone penetration tests were conducted at selected survey sites to determine the thickness of liquefiable layers in the Holocene interval as well as their liquefaction potential. Finally, a monitoring site was selected, and comprehensive subsurface investigations, including cross-hole seismic logging, were conducted. It was only on analysis of the cross-hole data that the phenomenon described here was recognized.

STUDY AREA

The study area is in the Cholame Valley in the Coast Ranges of central California (Figure 1). The field investigation was conducted on the flood plain of Cholame Creek. Fine-grained deposits with inter-bedded, discontinuous sand lenses underlie the flood plain (Holzer et al., 1986). The fine-grained material ranges from lean clay to sandy lean clay (CL) and has a water content ranging from 18 to 36 percent in the upper 23 m. The sand lenses range from silty sand (SM) to gravel with silt and sand (GW-GM). The water table is maintained within a few meters of the land surface by recharge from Cholame Creek, an intermittent stream.

METHODOLOGY

Nine seismic refraction surveys were conducted within an area of approximately 10 km^2 during June 1985 (Figure 1). The surveys were conducted with a Bison Model 1580 seismic recording system, which has a timing precision of 0.1 millisecond, and 50-Hz, vertical-component Bison geophones. Each survey line was 65 m in length, with geophones spaced 5 m apart. A hammer was struck vertically on a plate resting on the ground at the end of the geophone array to generate seismic energy. All surveys were reversed by striking at both ends of the geophone array. The P-wave arrivals were picked in the field on an oscilloscope to tenths of a millisecond and manually recorded. The seismograms were not permanently recorded. Travel-time curves were manually fitted to the data in the field, taking into account the reliability of the first-arrival picks.

The water table was measured at the middle of each seismic survey in an uncased, shallow boring made with a hand auger. The boring was drilled immediately after completion of the seismic survey. The boring was advanced until water began to flow into the hole, and the water level was monitored until it was static.

Cone penetration tests (CPT) were subsequently conducted at six of the seismic survey sites (Holzer et al., 1986) with a 10-cm^2 cone. The CPT measure both resistance to penetration of the tip of the cone and sliding frictional resistance along the sleeve of the cone. Penetration resistance was measured every 5 cm. The CPT technology is widely used to detect fine details of stratigraphy and to characterize textural properties of deposits.

Mok (1987) measured vertical profiles of P- and S-wave velocities during June 1986 by the cross-hole method in cased holes at SR-4, the site that was selected for the instrumented liquefaction array. Source and receiver holes for the cross-hole tests were 3 m apart, and measurements were made at depth intervals that ranged from 0.15 to 0.76 m to a depth of 11.9 m. Measurements were more tightly spaced near the sand layer to improve the evaluation of its susceptibility to liquefaction as based on S-wave velocity. Travel paths were corrected for inclination of the casings.

FIELD RESULTS

An example (SR-4) of a time–distance curve from the seismic refraction surveys is shown in Figure 2. The time–distance curves from all the seismic refraction surveys are comparable and suggest a two-layer velocity structure. Slopes of the legs of the travel-time curves are summarized and shown as apparent P-wave velocities in Table 1. The major difference between surveys is the total travel time, which indicates the depth to the top of the lower layer, varied between surveys. Slightly different velocities also were commonly measured when surveys were reversed, which indicates that the top of the lower layer is dipping. Apparent P-wave velocities of the upper and lower layers ranged from 333 to 396 m/second (average = 352 m/second) and from 1,250 to 1,700 m/second (average = 1,480 m/second), respectively. For reference, the P-wave velocity of saturated, unlithified sediment typically is greater than approximately 1,500 m/second (Schon, 1996).

Table 2 shows the results of fitting the travel times from each survey line with a two-layer velocity model with the constant layer velocities and a sloping interface (e.g., Dobrin, 1960). Actual P-wave velocities for the lower layer as based on the model ranged from 1,286 to 1,584 m/second (average = 1,465 m/second). The velocity used for the upper layer in each model was the average of the forward and the reversed velocities at the survey. The apparent dip of the top of the lower layer ranges from 0° at SR-2 and SR-9 to 1.9° at SR-7. Table 2 also shows the measured depth to the water table in the hand-augered boring at each survey and the estimated depth to the top of the lower layer at the center of each seismic survey as based on the sloping two-layer model. The depth to the lower layer reported in Table 2 is the average of the depths computed at the ends of the survey line.

Figure 3 shows the vertical profiles of P- and S-wave velocity measured at SR-4 by Mok (1987) using the cross-hole method. The depth to the water table at the time of the cross-hole measurements was 0.75 m. The P-wave velocity increases with depth, but it does not approach the velocity of saturated sediment until approximately 4.1 m. The P-wave velocities immediately beneath the water table are as low as 248 m/second. By contrast, the S-wave velocity increases only slightly with depth.

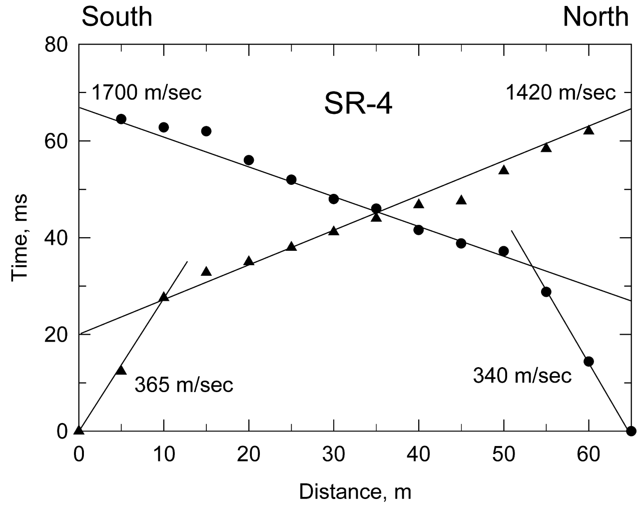

Figure 2. Time–distance curves from seismic refraction survey at SR-4.

SHALLOW VELOCITY STRUCTURE

The increase of the P-wave velocity in the upper 4.1 m as measured during the cross-hole investigation indicates that the two-layer, constant-velocity model used to interpret the travel-time curves of the surface seismic surveys is an oversimplification. The velocity inferred from the cross-hole tests increases approximately linearly from 288 m/second at 1.52 m to 1,556 m/second at 4.1 m. Only one velocity measurement (248 m/second) was made in the upper 1.5 m. The 5-m geophone spacing used in the surface seismic surveys is too large to determine if the velocity of the upper layer increases approximately linearly with depth. A linear depth dependence of velocity would cause curvature of the travel-time curves for the upper layer in the surface seismic surveys. Many of the travel-time curves for the upper layer, however, have three observation points and do not show curvature (e.g., see Figure 2).

Table 1. *Slopes of travel-time curves and total travel times from seismic refraction surveys.*

Survey No.	Upper Layer*		Lower Layer*		Total Travel Time (milliseconds)
	V_1 (m/second)	V_2 (m/second)	V_1 (m/second)	V_2 (m/second)	
SR-1	375	350	1,400	1,650	67
SR-2	352	333	1,325	1,325	81
SR-3	350	350	1,250	1,325	60
SR-4	365	340	1,420	1,700	67
SR-5	340	348	1,690	1,490	77
SR-6	340	350	1,680	1,470	72
SR-7	396	360	1,280	1,630	85
SR-8	348	358	1,650	1,320	74
SR-9	342	344	1,520	1,520	73

*V_1 and V_2, respectively, are the apparent compression-wave velocities with the seismic source on the south and north ends. All seismic arrays were oriented parallel to the northwest trending axis of the valley.

Table 2. *Two-layer velocity model parameters computed from seismic surveys and measured depths to water table from June 5–7, 1985.*

	Velocity (m/second)		Dip (°)*	Depth (m)	
Survey No.	Upper Layer	Lower Layer	Lower Layer	Top of Lower Layer†	Water Table
SR-1	363	1,514	1.2	4.9	1.7
SR-2	343	1,325	0.0	5.6	1.3
SR-3	350	1,286	0.5	2.0	0.8
SR-4	353	1,547	1.2	4.3	1.0
SR-5	344	1,584	−0.8	6.2	1.2
SR-6	345	1,514	−0.9	5.4	1.4
SR-7	378	1,433	1.9	7.8	2.1
SR-8	353	1,466	−1.6	5.4	>3.3
SR-9	343	1,520	0.0	5.6	3.4

*Dip is the apparent dip of the top of the lower layer. Positive dips are southeast; negative dips are northwest.
†Depth to top of lower layer is calculated at middle of survey.

The absence of curvature in the travel-time curves, however, does not preclude a more complex velocity structure in the upper layer. Based on the P-wave velocities measured in the cross-hole tests, the velocity structure of the upper layer may consist of two parts: an interval of approximately constant velocity overlying an interval with linearly increasing velocity. Synthetic travel-time curves computed by the authors for this velocity structure indicate that the interval with the large velocity gradient may not produce first arrivals in the surface seismic surveys. For example, the authors computed a synthetic travel-time plot for a surface seismic survey in which the upper layer was replaced with two layers: a 2-m-thick layer with a constant P-wave velocity of 250 m/second overlying a 2-m-thick layer with a velocity that increases from 250 to 1,500 m/second at 4 m. This velocity model does not produce first arrivals from the layer with the velocity gradient. All the arrivals from this layer are secondary, which results in synthetic travel-time curves similar to those curves shown in Figure 2 with two linear segments.

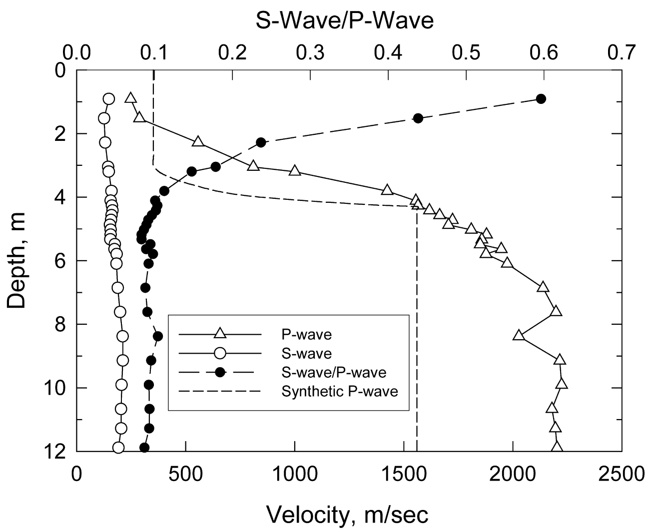

Figure 3. Depth profiles of compressional (P)- and shear (S)-wave velocity and ratio of S- to P-wave velocity at SR-4 as determined by cross-hole tests (data from Mok, 1987). Water table is at 0.75 m. The synthetic profile is predicted from the two-layer velocity model computed for the surface seismic survey at SR-4.

It also is worth noting that the higher P-wave velocities from approximately 3 to 4 m in the cross-hole test may result, in part, from refraction along the interface detected at 4.3 m in the seismic survey at SR-4. Effects from refraction on cross-hole measurements have been demonstrated by Hoar (1982). A simple calculation of first arrivals for cross-holes that are 3 m apart and that penetrate a 352-m/second, 4.3-m-thick layer overlying a 1,547-m/second layer reveals that the estimated velocities from 3 to 4 m will be higher than 352 m/second because of the refracted first arrival (see the synthetic profile in Figure 3).

DISCUSSION

The similarity of the velocity of the lower layer as detected in the seismic refraction surveys to that of saturated, nonlithified sediment suggests that the top of the lower layer is the water table. Such an interpretation based on P-wave velocity is common practice in shallow refraction seismology. This interpretation, however, is inconsistent with the water table as measured in the shallow auger borings. The water table at all the survey sites was above the top of the lower layer as determined by seismic refraction—the maximum difference equaled 5.7 m at SR-7. The two observations can be reconciled if the interval between the measured water table and the refracting interface is unsaturated. Such an interpretation is supported by the vertical profiles of P- and S-wave velocity as measured in the cross-hole test at site SR-4 (Figure 3). The P-wave velocities indicative of saturation are not reached until a depth of approximately 4.1 m,

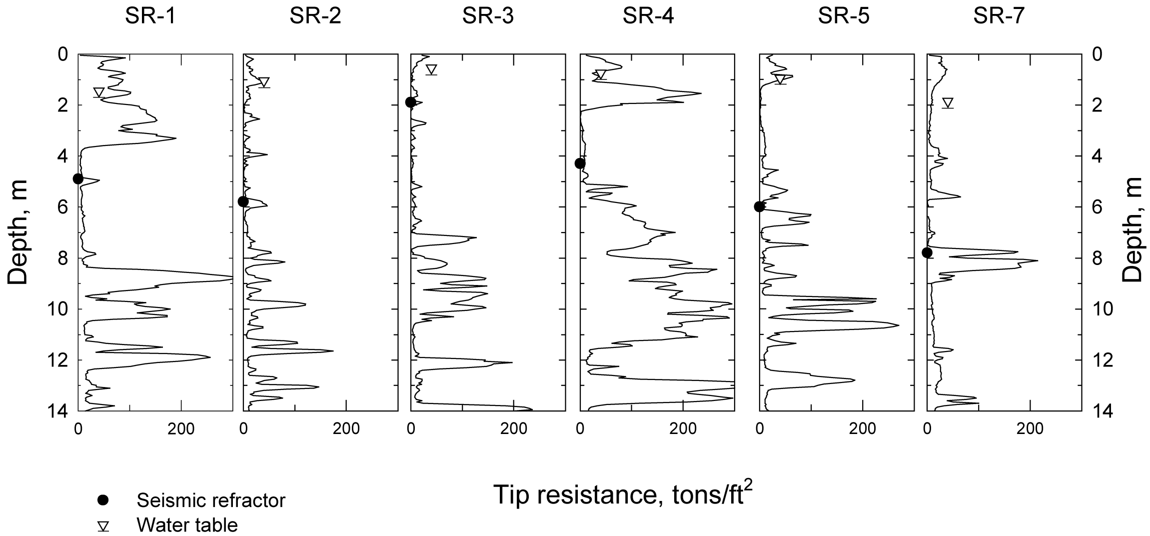

Figure 4. Cone penetration test of tip resistance to 14 m. Depth to lower layer as determined by seismic refraction and measured water table are indicated on each sounding.

despite a water table at 0.75 m. By contrast, S-wave velocity, which is insensitive to saturation, increases only modestly with depth over this interval. Additional evidence for saturation is provided by the variation with depth of the ratio of S- to P-wave velocity (Figure 3). The ratio decreases with depth to a constant value of approximately 0.1 at 4.1 m. For reference, the top of the saturated zone is inferred from the seismic refraction to be 4.3 m at this site (Table 2).

The authors dismiss alternative potential causes of the discrepancy. These include, first, that the top of the lower layer in the refraction survey is caused by a stratigraphically controlled contrast in acoustic impedance and, second, that the measured water table is for a perched groundwater system.

An acoustic impedance contrast that is related to stratigraphy can be evaluated indirectly with the CPT soundings at six of the survey sites (Figure 4). For reference, the higher CPT tip values here indicate coarser-grained sediment. The soundings collectively did not detect a stratigraphic horizon coincident with the top of the refracting layer. They also clearly did not indicate a simple two-layer model like that inferred from seismic refraction. Correlations between significant stratigraphic horizons and seismically determined depths were observed only at SR-4 and SR-7. At SR-3, the refraction depth is in a silty interval approximately 6 m above the first significant sand layer. Although depths to the refractor at SR-2 and SR-5 coincide with minor increases of CPT tip resistance, no refraction occurs from comparable units at SR-7, which suggests that the correlations at SR-2 and SR-5 are coincidental. Even at SR-4, where the top of the lower layer as determined by seismic refraction correlates with the top of a sand layer, the correlation probably does not result from a contrast in acoustic impedance caused by stratigraphy. The vertical profile of S-wave velocity (Figure 3) does not suggest a major contrast in acoustic impedance between the sand layer at 5 m and the overlying silty clay.

A perched water table can be dismissed directly at site SR-4 and indirectly throughout the study area. Water levels at SR-4 were identical in adjacent standpipe piezometers that were screened at 2.6 and 10.5 m (Holzer et al., 1986). The water level in the two piezometers also closely agreed with the water level in nearby Cholame Creek. On a valley-wide basis, water levels measured in all the borings in Cholame Valley are consistent with each other and define a shallow groundwater system flowing to the southeast (Figure 1)—the gradient that is expected on the basis of topography.

The authors are unable to resolve the differences in the shallow velocity structure inferred from the cross-hole tests and surface seismic surveys. The constant ratio of S- to P-wave velocity that begins at 4.1 m in the cross-hole data, however, compares favorably to the refracting interface at 4.3 m inferred from the seismic survey at SR-4. The agreement suggests that the simplified two-layer, constant-velocity model is a reasonable first approximation. The velocity structure above the top of the saturation zone warrants further detailed field investigation in future studies. An interval between the water table and the top of the saturation zone with a steep gradient of P-wave velocity can be caused by small changes in saturation and may not be detectable in travel-time curves that consider only first arrivals. Future refraction surveys conducted to estimate depth to the water table should take careful note of secondary arrivals for potential evidence of this interval.

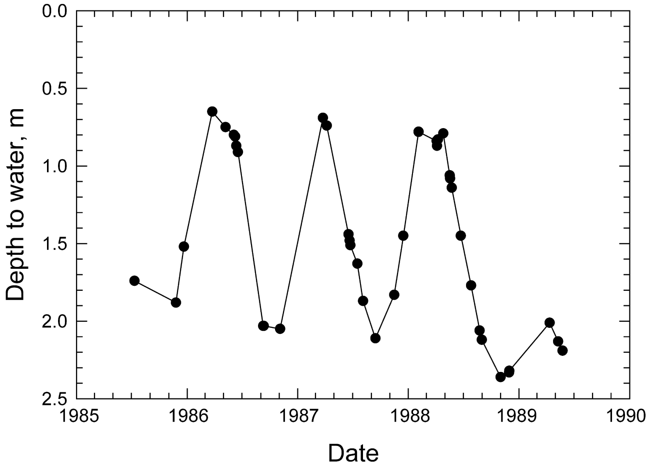

Figure 5. Hydrograph of water level in standpipe piezometer at SR-4. Depth to water is measured from the land surface (data from Holzer et al., 1986).

The cause of the unsaturation is speculative. Field conditions in the study area are natural, and the area is neither under irrigation nor heavily pumped. Monitoring of the water table from July 1985 to May 1989 at SR-4 indicated that water levels fluctuated seasonally from 0.65 to 2.36 m (Figure 5) from the land surface. Thus, the authors are inclined to attribute the unsaturation to unusually large seasonal declines associated with droughts manifested as dry winters (i.e., the normal period of natural recharge) in much of California. If valid, the explanation implies that resaturation of the deposit after water-table recovery may take years, because the last dry winter and, presumably, the largest recent water-table decline in the study area occurred during 1976 to 1977.

CONCLUSIONS

Discrepancies between water tables as measured in shallow borings and as inferred from surface seismic refraction surveys over flood-plain deposits in parts of Cholame Valley, California, indicate that an unsaturated zone, ranging in thickness from 1.2 to 5.7 m, is present beneath the water table. This condition is confirmed at one site by vertical profiles of P- and S-wave velocity as determined by cross-hole testing. The observations document unsaturation beneath a non-perched water table under natural conditions, and they demonstrate the potential use of seismic refraction to detect unsaturation beneath a non-perched water table.

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