is a viscous fluid. A saturated sand in a loose state can, from a sudden shock, also become a viscous fluid. This phenomenon is termed *liquefaction* and is of considerable importance when considering major structures (such as power plants) in earthquake-prone areas.

When soil water just dampens sand, the surface tension produced will allow shallow excavations with vertical sides. If the water evaporates, the sides will collapse; however, construction vibrations can initiate a cave-in prior to complete drying. The sides of a vertical excavation in a cohesive soil may collapse from a combination of rainfall softening the clay together with excess water entering surface tension cracks to create hydrostatic water pressure.

In any case, the shear strength of a cohesive soil can be markedly influenced by water. Even without laboratory equipment, one has probably seen how cohesive soil strength can range from a fluid to a brick-like material as a mudhole alongside a road fills during a rain and subsequently dries. Ground cracks in the hole bottom after drying are shrinkage (or tension) cracks.

Changes in the groundwater table (GWT) may produce undesirable effects—particularly from its lowering. Since water has a buoyant effect on soil as for other materials, lowering the GWT removes this effect and effectively increases the soil weight by that amount. This can produce settlements, for all the underlying soil "sees" is a stress increase from this weight increase. Very large settlements can be produced if the underlying soil has a large void ratio. Pumping water from wells in Mexico City has produced areal settlements of several meters. Pumping water (and oil) in the vicinity of Houston, Texas, has produced areal settlements of more than 2 meters in places. Pumping to dewater a construction site can produce settlements of 30 to 50 mm within short periods of time. If adjacent buildings cannot tolerate this additional settlement, legal problems are certain to follow.

## 2-5 ROUTINE LABORATORY INDEX SOIL TESTS

Some or all of the following laboratory tests are routinely performed as part of the foundation design process. They are listed in the descending order of likelihood of being performed for a given project.

### Water Content $w$

Water content determinations are made on the recovered soil samples to obtain the natural water content $w_N$. Liquid ($w_L$) and plastic ($w_P$) tests are commonly made on cohesive soils both for classification and for correlation studies. Water content determinations are also commonly made in soil improvement studies (compaction, using admixtures, etc.).

### Atterberg Limits

The *liquid* and *plastic limits* are routinely determined for cohesive soils. From these two limits the *plasticity index* is computed as shown on Fig. 2-2*a*. The significance of these three terms is indicated in Fig. 2-2*a* along with the qualitative effect on certain cohesive soil properties of increasing either $I_P$ or $w_L$. The plasticity index is commonly used in strength correlations; the liquid limit is also used, primarily for consolidation estimates.

The liquid and plastic limit values, together with $w_N$, are useful in predicting whether a cohesive soil mass is preconsolidated. Since an overconsolidated soil is more dense, the void



ratio is smaller than in the soil remolded for the Atterberg limit tests. If the soil is located below the groundwater table (GWT) where it is saturated, one would therefore expect that smaller void ratios would have less water space and the $w_N$ value would be smaller. From this we might deduce the following:

| | |
|---|---|
| If $w_N$ is close to $w_L$, | soil is normally consolidated. |
| If $w_N$ is close to $w_P$, | soil is some- to heavily overconsolidated. |
| If $w_N$ is intermediate, | soil is somewhat overconsolidated. |
| If $w_N$ is greater than $w_L$, | soil is on verge of being a viscous liquid. |

Although the foregoing gives a qualitative indication of overconsolidation, other methods must be used if a quantitative value of OCR is required.

We note that $w_N$ can be larger than $w_L$, which simply indicates the in situ water content is above the liquid limit. Since the soil is existing in this state, it would seem that overburden pressure and interparticle cementation are providing stability (unless visual inspection indicates a liquid mass). It should be evident, however, that the slightest remolding disturbance has the potential to convert this type of deposit into a viscous fluid. Conversion may be localized, as for pile driving, or involve a large area. The larger $w_N$ is with respect to $w_L$, the greater the potential for problems. The *liquidity index* has been proposed as a means of quantifying this problem and is defined as

$$I_L = \frac{w_N - w_P}{w_L - w_P} = \frac{w_N - w_P}{I_P} \tag{2-14}$$

where, by inspection, values of $I_L \geq 1$ are indicative of a liquefaction or "quick" potential. Another computed index that is sometimes used is the *relative consistency*,[2] defined as

$$I_C = \frac{w_L - w_N}{I_P} \tag{2-14a}$$

Here it is evident that if the natural water content $w_N \leq w_L$, the relative consistency is $I_C \geq 0$; and if $w_N > w_L$, the relative consistency or consistency index $I_C < 0$.

Where site evidence indicates that the soil may be stable even where $w_N \geq w_L$, other testing may be necessary. For example (and typical of highly conflicting site results reported in geotechnical literature) Ladd and Foott (1974) and Koutsoftas (1980) both noted near-surface marine deposits underlying marsh areas that exhibited large OCRs in the upper zones with $w_N$ near or even exceeding $w_L$. This is, of course, contradictory to the previously given general statements that if $w_N$ is close to $w_L$ the soil is "normally consolidated" or is about to become a "viscous liquid."

### Grain Size

The grain size distribution test is used for soil classification and has value in designing soil filters. A soil filter is used to allow drainage of pore water under a hydraulic gradient with

[2]This is the definition given by ASTM D 653, but it is more commonly termed the *consistency index*, particularly outside the United States.