Salt Water Intrusion
(West, Ch.15)
Outline: salt water intrusion

1. Concepts
2. Detection of salt water intrusion
The limited potable drinking water supply could be one of the most serious problems to a life support system. Drinking water standards established by the US Environmental Protection Agency (USEPA) in 1962 require that drinking water contain no more than 500 mg/L of total suspended solids (TSS), a common measure of salinity. Seawater contains approximately 30,000 mg/L of TSS, 60 times higher than the USEPA standard for drinking water. Therefore, it is evident that even a small amount of seawater can cause problems when mixed with freshwater reservoirs. Also, salinity in irrigation water can be detrimental to agriculture, reducing yields and killing crops.
Salt water intrusion

It is common in coastal areas, especially in over-populated towns.

In the land hydraulic system, when the fresh groundwater is withdrawn by pumping wells at a faster rate than it can be replenished, a drawdown of the water table occurs with a resulting decrease in the overall hydrostatic pressure. When this happens near an ocean coastal area, saltwater from the ocean intrudes into the freshwater aquifer (next Figure).
Salt Water Intrusion in Coastal Areas

Excess pumping of fresh water

Well contaminated with salt water

Original water table

Lowered water table

Fresh groundwater aquifer

Salt water intrusion

Original salt water interface

Salt Water

C. Ophardt c.1997
Definition of Salt water intrusion

In a more professional way:

Salt water intrusion is the migration of saltwater into freshwater aquifers under the influence of groundwater development. (Freeze and Cherry, 1979).
The Freshwater-Saltwater interface can be expressed by the Ghyben-Herzberg equation.

\[ h_s = \frac{\gamma_f}{(\gamma_s - \gamma_f)} h_f = \frac{1.0}{1.03 - 1.0} h_f \]

First the geometric relations are defined in the Figure, then we derived this equation.
Saltwater Intrusion

\[ H_f = H_s + h_f = H + h_s + h_f \]
\[ H_s = H + h_s \]
From the definition of hydraulic head, we have

Total Head = Pressure Head + Elevation Head

For the seawater and fresh water, separately, we have

\[ H_f = \frac{P_f}{\gamma_f} + H \]

\[ H_s = \frac{P_s}{\gamma_s} + H \]

In these equations
P is for pressure;
\( \gamma \) is the specific weight;
sub-indices f and s stand for fresh and sea, respectively.
The elevation head $H$ should be equal to a same value if we discuss at a particular point $P$. This point is chosen along the salt-fresh water interface. At any point along the salt water-fresh water interface, the hydraulic pressure should be a constant, or in another word, the pressure arose from the seawater side and the fresh-water side should be equal to each other, so we should have $P_f = P_s$. 
From the above equation we can have

\[ P_f = \gamma_f (H_f - H) \]

\[ P_s = \gamma_s (H_s - H) \]

then at the interface we get

\[ \gamma_f (H_f - H) = \gamma_s (H_s - H) \]

By the geometric relations (see the Figure)

\[ H_s = H + h_s \]

\[ H_f = H_s + h_f = H + h_s + h_f \]
we get

\[ \gamma_f (H + h_s + h_f - H) = \gamma_s (H + h_s - H) \]

so we get

\[ \gamma_f (h_s + h_f) = \gamma_f h_s + \gamma_f h_f = \gamma_s h_s \]

and

\[ h_s (\gamma_s - \gamma_f) = \gamma_f h_f \]

Finally

\[ h_s = \frac{\gamma_f}{(\gamma_s - \gamma_f)} h_f = \frac{1.0}{1.03 - 1.0} h_f \]

This equation is the so-called Ghben-Herzberg equation.
It shows that the change of seawater thickness in the aquifer depends on the change of fresh-water thickness. However, the increase of saltwater thickness has been amplified by as many as 33 times, depending on the specific weight of the freshwater and the seawater. For example, if the specific weights is unity for freshwater and 1.03 for seawater, the ration of the factor is 33. It means that 1-foot freshwater drawdown (or say 1-foot decrease in freshwater thickness) will induce 33 feet decrease of $h_s$, i.e., the elevation of the saltwater-freshwater interface will upraise 33 feet.
Change of saltwater/freshwater interface caused by sea level rise (Liu, 2003).
The Ghyben-Herzberg relation states that a one-meter height of freshwater above sea level assures 33 meters of freshwater below sea level. Likewise, a 0.5 m rise in sea level causes a 17 m reduction in the freshwater thickness (next Figure). Under conditions of climate change, the rate of sea level rise is sufficiently slow so that groundwater heads at or near the coast will increase to respond the sea level rise, rather than remaining at their present position. Nevertheless, the rise in the water table near the sea boundary will not be necessarily associated with a similar rise in water levels at the land side, as seen in the Figure. Consequently, the gradient of the water table (for the unconfined aquifers) or the piezometric head (for the confined aquifers) is reduced and hence more intrusion can be expected.
Four technical components necessary to provide successful management of the saltwater interface.
Seismic Refraction

ASTM D 5777

Note: \( V_{p1} < V_{p2} \)

Determine depth to rock layer, \( z_R \)

\[ z_R \]

Source (Plate)

Vertical Geophones

\[ t_1, t_2, t_3, t_4 \]

Soil: \( V_{p1} \)

Rock: \( V_{p2} \)
Principle of the seismic refraction method. Travel time curves for direct waves, critically refracted waves (also called head waves), late refracted arrivals, and reflected waves are shown by numbers 1-4, respectively. The well-known Snell’s law governs the refraction and reflection of the incident waves at a velocity interface.