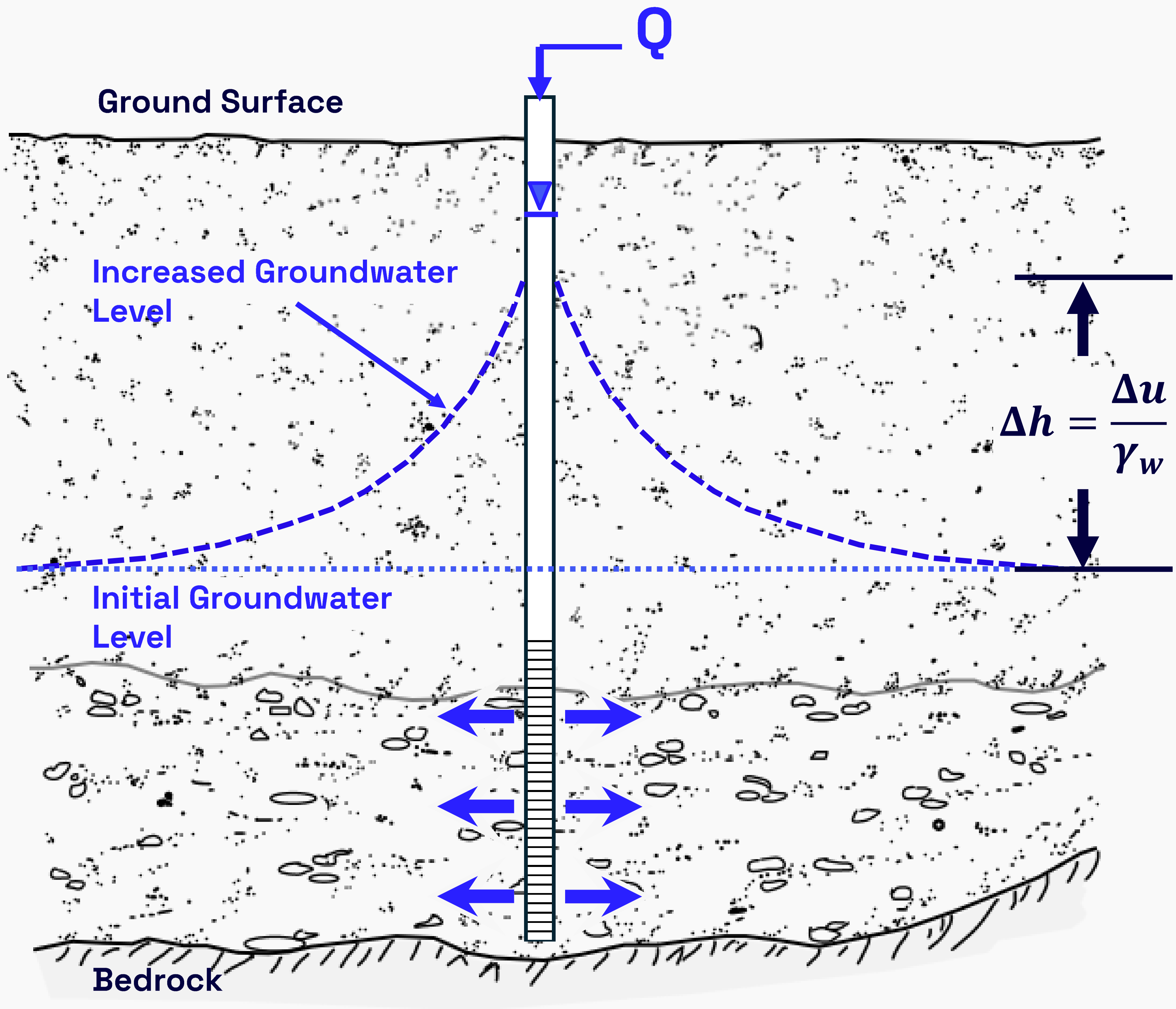
Estimating Maximum Injection Pressure for Aquifers



Shear Failure Threshold (matrix failure)

$$\Delta u_{fail} = \frac{1}{2}\sigma'_h$$

When to use it

To estimate the maximum allowable formation (aquifer) pore pressure during injection.

This helps reduce the risk of ground heave and avoid damage to infrastructure and buried utilities.

Use the injection rate–pressure relationship to help estimate how many injection wells you will need for a project.

Important to note

This injection limit applies to formation (aquifer) pressure, not pressure inside the injection well.

Pressure measured inside the injection well is often much higher than aquifer pressure because of well losses and other well-hydraulic effects.

Measure aquifer pressure using observation wells or piezometers.

Typical Applications

- Aquifer Storage & Recovery
- Reinjection from dewatering
- Open Loop Geothermal Injection

What you will need

- Site lithology & unit weights (unsat/sat) for overburden load
- Soil friction angle (ϕ) for the relevant materials
- Initial groundwater levels and the expected change due to injection.
- Screen depth/interval

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Equations & Calculation Procedure

Step 1: Calculate the soil load above the screen

$$\sigma_v = \sum_i \gamma_i \, h_i$$

Step 2: Calculate the initial groundwater pressure at the screen

$$u_0 = \gamma_w \, h_w$$

Step 3: Calculate the initial vertical load carried by the soil grains

$$\sigma'_v = \sigma_v - u_0$$

Step 4: Calculate the initial horizontal load carried by the soil grains

For normally consolidated soils:

$$\sigma'_h = K_0 \, \sigma'_v \text{ where } K_0 = 1 - \sin\phi$$

For over-consolidated soils:

$$\sigma'_h = \sigma'_v (1 - \sin\phi) \, (OCR)^{\sin\phi}$$

Step 5: Choose Design limit Criteria

1) pressure increase before the soil grains start to fail: $\Delta u_{fail} = \frac{1}{2} \sigma'_h$

2) Pressure increase that can start fractures: $\Delta u_{frac} = \sigma'_h$

3) Pressure increase that can fluidize the soil: $\Delta u_{fluid} = \sigma'_v$

Symbols Used

Symbol	Meaning	Typical units
Δu	Increase in groundwater pressure caused by injection	kPa
σ_v	Soil load above the top of screen from soil weight [total vertical stress]	kPa
u_0	Initial groundwater pressure at the top of screen [pore pressure]	kPa
σ'_v	Vertical load carried by the soil grains at the top of screen [vertical effective stress]	kPa
ϕ	Friction angle of the soil [effective friction angle]	°
K_0	Horizontal load ratio before injection (horizontal/vertical) [at-rest earth pressure coefficient]	–
σ'_h	Horizontal load carried by the soil grains at the top of screen [horizontal effective stress]	kPa
OCR	Over-consolidation ratio (only if using OC equation)	–
Δu_{fail}	Pressure increase that starts grain-structure failure – the estimated damage threshold [matrix failure]	kPa
Δu_{frac}	Pressure increase that can start fractures [fracture initiation]	kPa
Δu_{fluid}	Pressure increase that can fluidize the soil where grains carry ~ zero load [effective vertical stress → 0]	kPa
γ_w	Unit weight of water (used to compute from head)	kN/m^3
γ_i	Unit weight of soil layer i (dry or saturated, as applicable)	kN/m^3
h_i	Thickness of soil layer	m
h_w	Height of water above the top of screen (to water level/potentiometric surface)	m

Example Calculation

Given:

An injection well is required at a site underlain by a layered sand and gravel aquifer. The stratigraphy consists of 6 m of sand over 3 m of gravel. The aquifer is unconfined, with an initial groundwater level 5 m below ground surface. The top of the well screen is at the top of the gravel layer, 6 m below ground surface. The sand and gravel are normally consolidated. The sand has an effective friction angle (ϕ) of 35°. The sand unit weights are 18 kN/m³ (unsaturated) and 20 kN/m³ (saturated).

Task:

Calculate the maximum rise in groundwater level (head increase) at the screen before shear failure occurs. Do this as an initial assessment without applying a safety factor.

Step 1: Calculate soil load above the screen $[\sigma_v]$

Above the screen you have:

- Unsaturated sand: 0–5 m → 5m
- Saturated sand: 5–6 m → 1m

$$\sigma_v = (18)(5) + (20)(1) = 90 + 20 = 110 \ kPa$$

Step 2: Calculate initial groundwater pressure at the screen $[u_0]$

Water head above screen:

$$h_w = z - z_{wt} = 6 - 5 = 1 \ m$$
$$u_0 = \gamma_w h_w = (9.81)(1) = 9.81 \ kPa$$

Example Calculation

Step 3: Calculate vertical load carried by soil grains $[\sigma_v']$

$$\sigma_v' = \sigma_v - u_0 = 110 - 9.81 = 100.19\ kPa$$

Step 4: Calculate lateral load carried by soil grains $[\sigma_h']$

$$K_0 = 1 - \sin(35°) \approx 1 - 0.5736 = 0.4264$$

$$\sigma_h' = K_0\sigma_v' = (0.4264)(100.19) = 42.74\ kPa$$

Step 5: Calculate shear Failure Threshold (matrix failure) $[\Delta u_{fail}]$

$$\Delta u_{fail} = \frac{1}{2}\sigma_h' = 0.5(42.74) = 21.37\ kPa$$

Assessment: Convert Δu_{fail} **to an equivalent head change**

$$\Delta h_{fail} = \frac{\Delta u_{fail}}{\gamma_w} = \frac{21.37\ kPa}{9.81\ kPa/m} = 2.18\ m$$

For this example, the aquifer injection pressure limit is 21.37 kPa, which corresponds to a 2.18 m rise in groundwater level (head). Using this maximum allowable head increase, you can estimate the maximum injection rate with an appropriate groundwater flow model.