HYDROGEOLOGISTS AND GEOTECHNICAL ENGINEERS – LOST WITHOUT TRANSLATION

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1 INTRODUCTION

Hydrogeologists and geotechnical engineers typically reach their professions by different academic routes – the former mostly from geology and the latter mostly from civil engineering. For historical reasons these disciplines have adopted substantially different words to express and define what are identical physical and mathematical facts and concepts. The net result is that much of the time professionals of the one kind don't know what the other kind are talking about.

In addition these professions have adopted different heuristics to make their tasks easier, heuristics being:

> *"…simplified rules of thumb that make things simple and easy to implement. Their main advantage is that the user knows they are not perfect, just expedient, and is therefore less fooled by their powers. They become dangerous when we forget that".*
>
> (Taleb, 2012)

Thus geotechnical engineering is based substantially on the theory of linear elasticity, even though real geotechnical materials are neither elastic, nor linear. Hydrogeologists in turn depend substantially on two heuristic classifications, these being the notions of:

- 'aquifers', and their opposites; 'aquicludes' and 'aquitards', and
- "confinement' and its inverse 'connectivity'.

It is the purpose of this paper to connect the languages of hydrogeology and geotechnical engineering, and also to demonstrate that the heuristics adopted, can have important negative consequences. This accords with the point made by Daniel Kahneman:

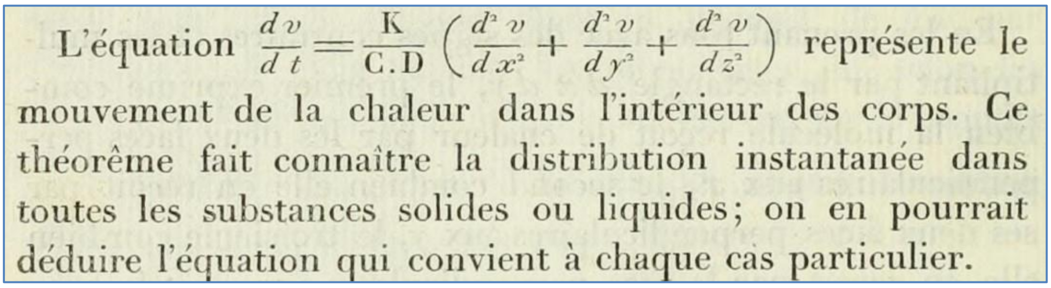
> *"This is the essence of intuitive heuristics; when faced with a difficult question, we often answer and easier one instead, usually without noticing the substitution."*

We deal with words and concepts that are particular to hydrogeology, being Specific Storage, Hydraulic Diffusivity, Specific Yield, Specific Retention and Transmissivity, and which often mystify civil engineers with conventional training in soil mechanics. By translating these hydrogeology terms to those understood by engineers we hope to help communications between these closely aligned professionals.

We also trace the etymology of the classification of 'aquifers' and 'confinement', and the development of the current hydrogeologist's heuristics, and suggest that, in some situations, these heuristics are misleading, and no longer necessary.

2 MATHEMATICAL FUNDAMENTALS THAT ALLOW THE TRANSLATIONS

Boussinesq (1877 and 1902) established the mathematics of transient groundwater flow through porous media by combining the differential equation of flow with the equation of continuity. The resulting equation is the same as the heat equation determined by Fourier (1807, 1822) – see Figure 1. The only difference is that gravity plays a role in groundwater flow.



L'équation $\frac{dv}{dt} = \frac{K}{C.D}\left(\frac{d^2v}{dx^2} + \frac{d^2v}{dy^2} + \frac{d^2v}{dz^2}\right)$ représente le mouvement de la chaleur dans l'intérieur des corps. Ce théorême fait connaître la distribution instantanée dans toutes les substances solides ou liquides; on en pourrait déduire l'équation qui convient à chaque cas particulier.

Figure 1: The heat equation as published by Fourier(1822).

There are about as many versions of the transient groundwater flow equation as there are publications on the topic, with authors choosing to use different symbols and words for the same thing[1]. We consider that a neat presentation of the relevant equations are by Biot (1941).

The equation for flow in three dimensions is:

$$\nabla h^2 = \frac{1}{c}\frac{\partial h}{\partial t} \tag{1}$$

where:

h = potentiometric (hydraulic) head = $\frac{p}{\gamma_w} + z$

t = time, (T)

∇ = Laplace operator

c = Consolidation Coefficient (L^2/T)

If there is full saturation the Consolidation Coefficient is:

$$c = \frac{k}{\alpha\gamma_w} \quad (L^2/T) \tag{2}$$

where

k = Hydraulic conductivity (L/T)

γ_w = Unit weight of water (M/L^2T^2)

α = Compressibility of the bulk ground (LT^2/M) $= \frac{(1+\nu)(1-2\nu)}{E(1-\nu)}$ (3)

ν =Poisson's Ratio

E =Young's Modulus (M/LT^2)

Equations 1 to 3 are for any transient flow problem in a saturated compressible medium. They assume Darcy seepage, small strain theory, linear elasticity and permeability independent of effective stress. They also assume that water in incompressible, although compressibility of the pore fluid requires only a minor modification to Equation 1.

These assumptions are reasonable for most civil engineering applications including assessing macro-seepage through fractured rock masses. The equations can be generalised for anisotropy and for partly-saturated conditions.

Equation 1 allows one to perform key translations.

Firstly, Biot's Consolidation Coefficient is:

- identical to **Hydraulic Diffusivity** as used in the hydrogeology literature,
- equivalent to Thermal Diffusivity in the heat equation, and
- the same as Terzaghi's Coefficient of Consolidation.

Hydrogeologists use three other terms in association with Equation 1. They and their translations are:

- **Specific Storage** (also called **Specific Storativity**) - being the product of compressibility and unit weight of water, viz:

$$S_s = \alpha\gamma_w \quad (1/L) \tag{4}$$

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[1] For example, in a simple matter, it is found that the parameters for permeability and hydraulic conductivity are termed, and symbolised as:

- κ *'Intrinsic Permeability'* L^2 (Verruijt1970)
- K_i *'Permeability'* L^2 (Kresic 2007)
- k *'Coefficient of Permeability'* L/T (Verruijt1970 and Biot 1941)
- K *'Hydraulic conductivity'* L/T (Kresic 2007)

- **Storage Coefficient** (also called **Aquifer Storativity** or **Storativity**) – being the product of **Specific Storage** and the thickness of a defined 'aquifer' (b), viz:

$$S = S_s b \text{ (unitless)} \tag{5}$$

As a word of caution it must be noted that at depths dealt with in reservoir engineering for the oil industry, compressibility of pore fluids becomes significant, with the result that the equations for Specific Storage and Storativity are different to those given above, but which are applicable to most civil and mining engineering projects.

Hydrogeologists also make much use of the term Transmissivity, which is simply Hydraulic Conductivity multiplied by the thickness of a defined 'aquifer': T = kb.

A particular case has to be addressed where there is a phreatic surface[2] in the groundwater regime under consideration. When the phreatic surface changes water either drains from the ground above the surface as the surface lowers, or water may go into storage as the surface rises. This is the situation hydrogeologists refer to as an **Unconfined Aquifer**. Computations in this situation require modifications to Equation 1, requiring a measure of what Meinzer (1932) called **Effective Porosity**[3] and which most hydrogeologists call the **Specific Yield**[4] In soil mechanics terminology this parameter has been called **Specific Porosity**[5].

3 DERIVATION OF PARAMETERS

Given the above translations it can be seen that, for the assumption of linear behaviour, it is only necessary to determine five parameters for each material type, namely:

- Mass Young's Modulus of a jointed rock mass, or the mass Young's Modulus of the soils in question[6].
- Mass Poisson's Ratio.
- Effective Porosity.
- Hydraulic Conductivity.

Geotechnical engineers can usually make reasonable assessments of the likely range of Young's Modulus values; and Poisson's ratio (which is usually between 0.15 and 0.4). Effective Porosity can also be assessed within reasonable ranges, being close to true porosity for gravel, and almost zero for clays and mudstones.

However, in-situ permeability values, and anisotropy of permeability, are usually only known to orders of magnitude. In the example given above, this uncertainty changes a benign 200 years to an unacceptable 20 years.

In the near horizontally bedded Triassic strata of the Sydney Basin, which have been investigated for very many underground mining and civil engineering projects, there are very wide ranges of measured hydraulic conductivity values, and even wider ranges adopted by analysts (see Figure 2). It can be seen that there are differences of up to 3 orders of magnitude in respect to adopted permeability values. It can also be seen that, for the Bald Hill Claystone, there is no correlation between the field tests and adopted parameters.

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[2] The phreatic surface is at atmospheric pressure; some distance above the surface where pore pressures are negative, air is sucked into the voids causing partial saturation. This is a highly non-linear situation where hydraulic conductivity changes and high matric suctions are generated.

[3] "volume of interconnected pore space that allows free gravity flow of groundwater" (Kresic, 2007).

[4] "that volume of water in the pore space that can freely drain due to change in the hydraulic head" (Kresic 2007).

[5] Bishop (1967).

[6] Measured from strains under change of effective stress.

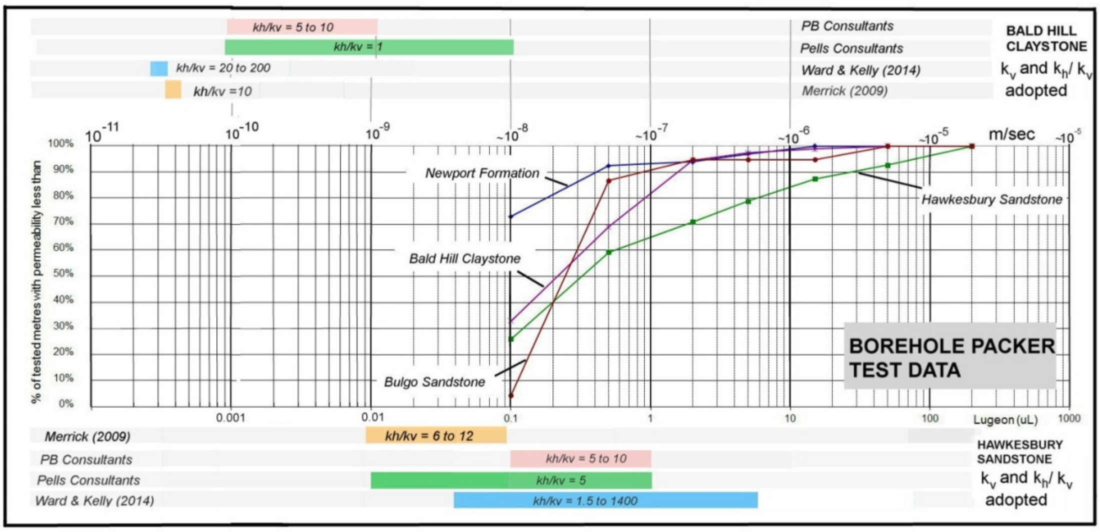


Figure 2: Differences in hydraulic conductivity parameters adopted in the Sydney Basin compared with laboratory tests.

In addition there is the observation that permeability values decrease with depth in each stratigraphic unit (Tammetta and Hawkes, 2009).

Therefore, it is obvious that uncertainties in hydraulic conductivity values dominate computations of groundwater flow quantities and depressurisation, these being independent factors. Sensitivities to compressibility and volumetric water content is secondary.

It has already been noted that the above parameters are for assumed linear behaviour. With the power of modern numerical analyses one is not limited to the linear assumption and usually assessments have to be made of:

- Hydraulic conductivity versus pore pressure (for negative pore pressures).
- Volumetric water content versus pore pressure.

The first of these two functions is very difficult to know and should be studied by parametric variation for a particular analysis. Such parametric investigations are essential for a particular project to obtain an understanding of the impacts of the engineering heuristic of linear behaviour.

4 THE HEURISTICS OF HYDROGEOLOGY

4.1 The Key Problem

A key problem in hydrogeology was that for about 180 years Equation 1 could not be solved for most real situations. So, using Kahneman's language, *"when faced with a difficult question, we often answer an easier one instead..."*.

This difficulty went hand in hand with the earliest work in hydrogeology which was concerned with understanding the artesian groundwater resources of France and Italy.

4.2 Development of Understanding of Artesian Groundwater

The word *'aquiféres'*, meaning liquid bearing, was used by the French Zoologist, Lamarck (1830), in describing vessels of the lungs, some being air-bearing (*trachées aėriféres)* and some carrying blood (*trachées aquiféres).*

The same word, *aquiféres*, was then used in 1835 by Lamarck's colleague, Francois Arago. Writing in the *Annuaire Le Bureau des Longitudes (p225*), in regard to artesian bores and springs, he said:

> *"Let's remember now the way rain waters penetrate some stratified land layers; let's keep in mind that it's only on the hill slopes or at their crest that the section of the layers is exposed; that this is their water intake; so it always occurs at height. Let's think, in addition, that these* ***aquifer*** *layers, after going down along the slope of the hills that broke them a long time ago by raising them, extend horizontally or almost horizontally across the plains and that they are often sort of enclosed between two impermeable layers of clay or rock. So we will conceive the existence of underground* ***aquifers*** *that are, naturally, in the same hydrostatic conditions as the*

> *commonplace ducts, whose soutérazi give us a model. And that a borehole drilled in the valleys, through the upper ground down to and including the highest of both waterproof layers, within which the* ***aquifer*** *is enclosed, will become the second branch of the U-shaped pipe we mentioned at the beginning of this chapter, or if you like of an inverted water trap, or, even better, of a soutérazi. The fluid will rise inside this borehole, to the height the corresponding* ***aquifer*** *attains on the hillsides it originated from.*
>
> *From there, everyone should understand how, on a given horizontal ground, underground waters, placed at different levels, can have different upwards forces; from there, everyone will explain why the same* ***aquifer*** *rushes here at great heights, while it fails to reach ground level further. Simple level inequalities will become the sufficient cause, the natural cause of all these inconsistencies."*

By way of explanation, the word *soutérazi* relates to the square obelisks, or pillars, erected in valleys between the supply reservoir and the city of Constantinople (see Figure 3), such that "*the level of the top of every successive pillar varies analogous to an inclined plan commencing at the mountains*" (Matthew, 1835).

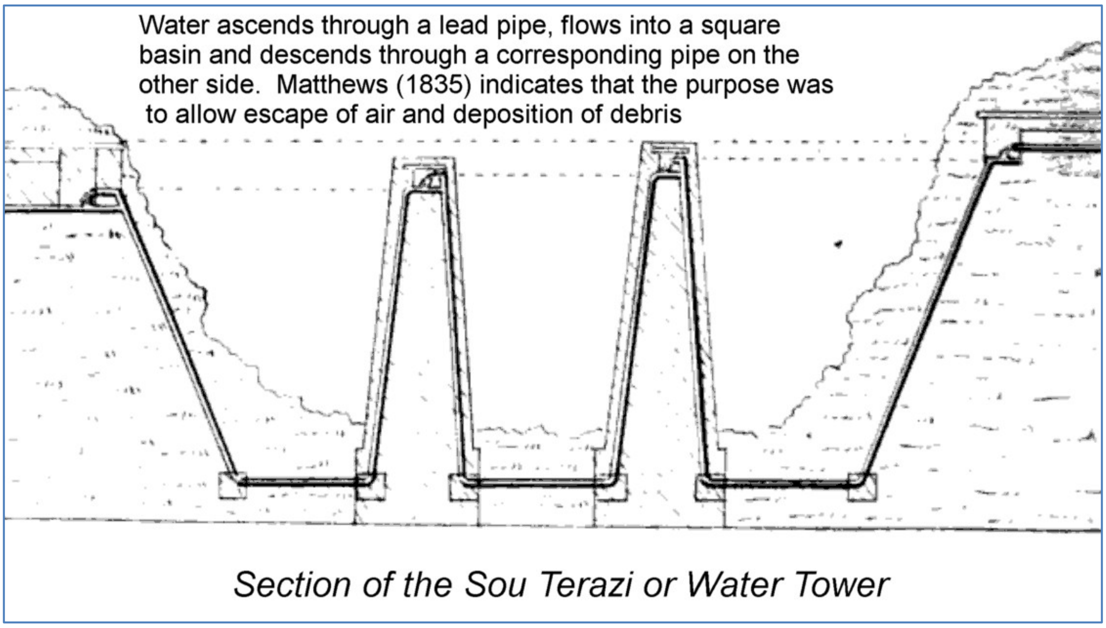
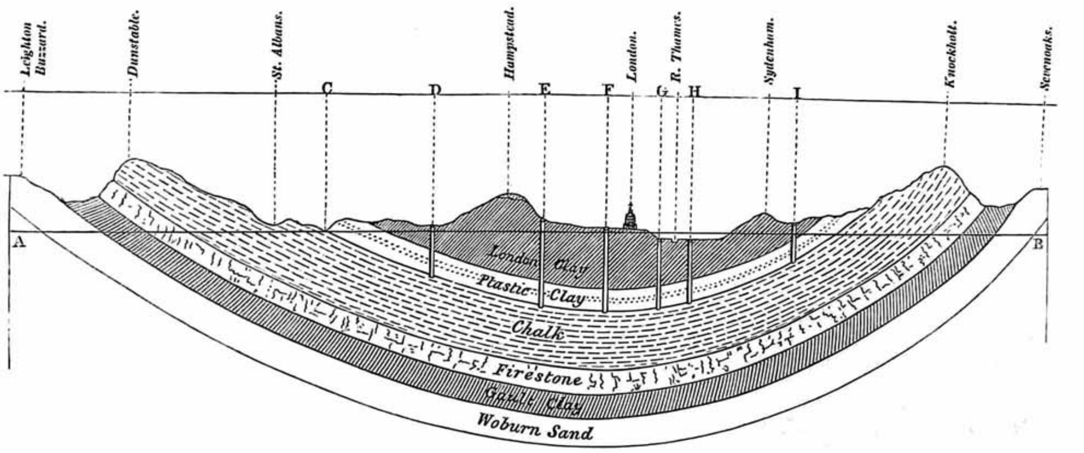


Figure 3: Soutérazi along the water supply to Constantinople.

It is clear from Arago's work that he intended the word *aquifer* to have a similar connotation to *aqueduct*, and to imply the characteristics of a conduit. The purpose was to explain artesian springs, a matter which at that time was somewhat controversial. The concept allowed linkage to the known science of hydrostatics (Pascal, 1647), and the conveyance of city water supplies as described by Darcy (1856) and Matthews (1835).

In 1836, the Rev William Buckland, who was familiar with Arago's work, produced a cross-section showing the genesis of artesian wells beneath London (see Figure 4). He did not use the word *aquifer*.



Section shewing the cause of the rise of water in Artesian Wells in the basin of London.

Figure 4: The artesian wells of London, William Buckland, 1836.

We do not know when the terms *aquitard and aquiclude* were first used. They do not appear in the works of Meisner (1923 and 1928), but what became important is that he encapsulated the essence of these words in the concept of *'confinement'* of an aquifer. Thus in 1923 he wrote:

> *"… **serves to confine** the water of the Lissie gravel under artesian pressure"*
>
> (Meissner, 1923, p 308)

In 1928 he presented this idea diagrammatically as reproduced in Figure 5.

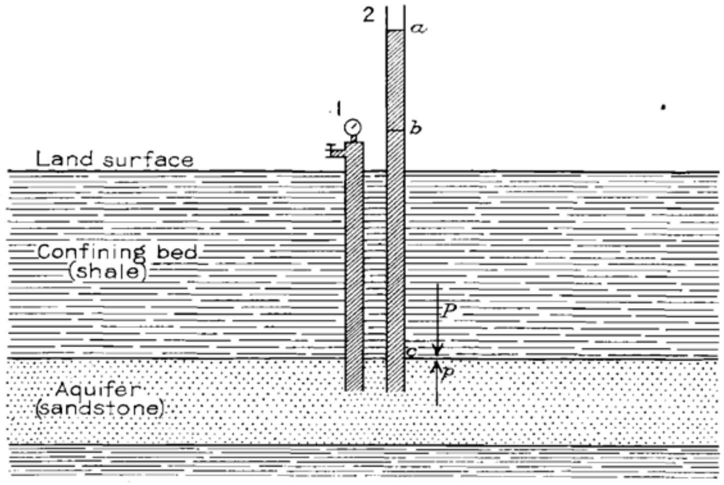


FIG. 1. Ideal section showing pressure relations in an artesian aquifer.

Figure 5: Confined aquifer, Meisner, 1928.

In the real world, the differentiation between aquicludes, aquitards and aquifers is unclear. There is no accepted standard of measurement which differentiates or defines them in relation to geological formations which are a continuum of materials with wide ranging properties in regard to how water is stored and transmitted. There is also no accepted standard of measurement which differentiates or defines whether a portion of ground is 'confined' or 'unconfined'.

This confusion was unacceptable to C V Theis, who, 52 years after his famous paper on transient flow to wells (Theis, 1935), and shortly before his death, dictated the last changes to a paper titled, "Aquifers, Ground-Water Bodies and Hydrophers" . In this he said:

> *"Thus, "aquifer" has been used in so many different senses by so many people to express their own particular ideas that it has become an Alice-in-Wonderland word that means just what the author says it means. Worst of all, the author practically never tells us what he means. It has been used in so many different ways that it must be abandoned entirely as a scientific word or alternately to express* only *the original usage of it without any relation to the water table ….."*
>
> (Theis, 1987)

4.3 The Co-Development of Approximate Solutions to the Diffusion Equation

The first mathematical heuristic applied to solving the diffusion equation for groundwater (Equation 1) was by Dupuit (1863) who postulated that groundwater flows horizontally in an unconfined aquifer, and that the groundwater discharge is proportional to the saturated aquifer thickness[7]. The essence of the assumptions is that equipotentials are vertical.

From this, Dupuit derived an approximate equation for flow to a well, namely:

$$Q = \pi k \frac{(H^2 - h_0^2)}{\log(L/R)} \tag{6}$$

where the terms are shown in Figure 6, and L is "*le rayon du massif filtrant*".

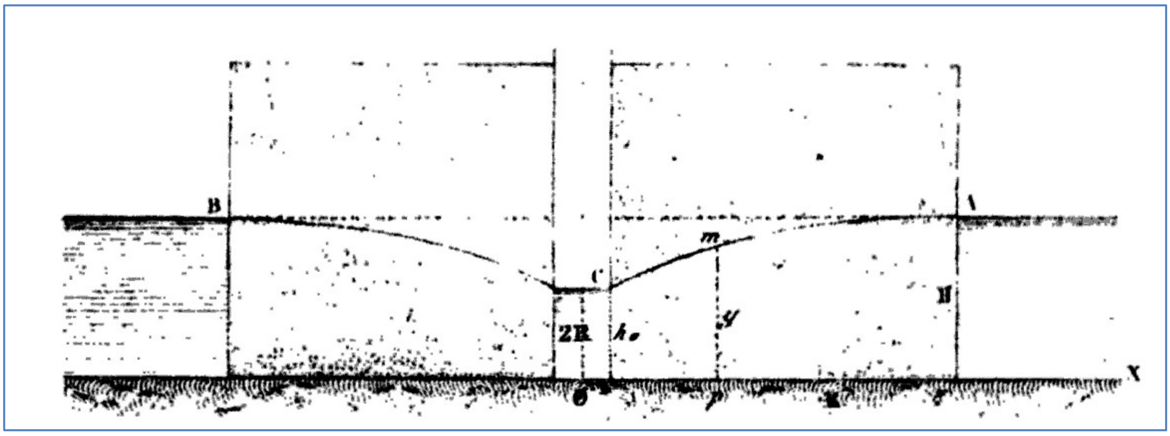


Figure 6: Dupuit (1863) Figure 65; analysis of flow to a well in a sand island.

Obviously the error arising out of the Dupuit assumption relates directly to the degree to which the actual flow pattern diverges from horizontal, meaning equipotentials are not vertical.

Thiem (1870) made the equation useful by showing that beyond a certain distance from a well, drawdown of the potentiometric surface becomes negligible, and Theis (1935) extended the solution to non-steady state in a, so-called, confined aquifer.

All of these reinforced the heuristic of horizontal flow, and reinforced the use of aquifers, aquicludes and Transmissivity.

The impact of Dupuit's heuristic grew to the point where now, the most widely used 3D groundwater software, MODFLOW, was created within the framework of that heuristic.

There is no doubt that the Dupuit assumption was, and is, valuable where the prime purpose is furnishing a supply of groundwater. But the simplifications have locked in obeisance to horizontal flow and have fed poor understanding of groundwater depressurisation. The fundamental difference between flow quantity, and depressurisation has become lost. Depressurisation and drawdown became synonyms, which they are not.

Depressurisation, involves changing the shapes of equipotentials; typically changing them from near vertical to near horizontal.

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[7] Dupuit actually addressed flow to a well within a circular island of sand.

5 DISCUSSION

We consider that the word differences that have developed between hydrogeologists and geotechnical engineers for what are exactly the same concepts and parameters is an accident of history arising from a combination of the early studies of artesian groundwater systems, and inability to solve the diffusion equation without invoking grossly simplified boundary conditions.

We consider that modern computational methods render many of the historical terms, and analytical methods obsolete, and have led to a contagion of error when considering depressurisation impacts of tunnels, deep basements, open pit mines and underground mines. These impacts can be assessed, not precisely, but within reason, by disregarding the heuristic of horizontal flow, and by heeding the advice of Theis (1987) to the effect that the use of the word aquifer "*should be abandoned entirely as a scientific word or alternately to express only the original usage*".

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