Geotechnical and hydrogeological characterization of residual soils in the vadose zone

by

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ABSTRACT

Groundwater is an important natural resource and ought to be protected. Groundwater recharge and contamination are two important aspects in groundwater management. Both these aspects apply to the vadose zone.

The research aimed to narrow the knowledge gap between practising geohydrologists and engineering geologists, both frequently involved in vadose zone investigations for geohydrological and engineering purposes respectively.

The vadose zone is the portion of the geological profile above the groundwater surface and is usually characterised by unsaturated conditions. Matrix forces counteract the force of gravitation to hold liquid in the porous medium and are reflected by hydraulic heads lower than atmospheric pressure (suction). The unique relationship between soil-water content and suction is presented by soil-water characteristic curves.

Flow of liquids is directly proportional to the hydraulic gradient and the hydraulic conductivity and is affected by the geometric properties of the pore channels. In unsaturated soils, flow is governed by both matrix and gravitational forces. Preferential flow is the process by which water and solutes move along preferred pathways through a porous medium.

Important hydrogeological properties, such as porosity, hydraulic conductivity and soil-water retention characteristics, can be estimated from geotechnical data. Unsaturated hydraulic conductivity can also be estimated from soil-water characteristic curves and saturated hydraulic conductivity.

The experimental procedures comprised analyses of existing hydrogeological data, laboratory tests and field experiments. The geotechnical data were used to predict important hydrogeological properties and these predictions were compared to experimentally derived hydrogeological properties. The effects of preferential flow and soil variability were also investigated.

Predictions of porosity, hydraulic conductivity and soil-water retention characteristics lack precision, owing mostly to the natural variability in hydrogeological properties and inherent errors of the empirical models. Accurate predictions of unsaturated hydraulic conductivity were based on experimentally derived saturated hydraulic conductivity and soil water characteristic data.

The study area is located in Midrand and is underlain by granitoid rocks that had been subjected to a number of geomorphologic events. The land system classification approach was used to delineate the hydrogeological units. The different hydrogeological characteristics can be attributed mainly to the position of the hydrogeological units in respect of the topographical setting, the geomorphologic history and the underlying geology. A conceptual hydrogeological model was constructed for each of the hydrogeological zones and its significance in respect of groundwater recharge and vulnerability discussed.

The research has shown that geohydrological properties can be estimated from geotechnical data with various degrees of accuracy. Predictions of hydraulic conductivity, soil water retention characteristics and porosity are not suitable for site-specific investigations, but it can be used during the feasibility phases. In cases where saturated hydraulic conductivity and soil-water retention characteristics have been experimentally derived, estimations of unsaturated hydraulic conductivity are adequate for site-specific investigations. The land system approach can be used to delineate areas of similar geohydrological characteristics and these can be used in the compilation of aquifer vulnerability and groundwater recharge maps.

(478 words)

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Die geotegniese en hidrogeologiese karakterisering van residuele gronde in die vadose sone

deur

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UITTREKSEL

Grondwater is 'n belangrike natuurlike hulpbron en behoort beskerm te word. Die bepaling van grondwateraanvulling en die omvang van grondwaterkontaminasie is twee belangrike aspekte van grondwaterbestuur. Beide hierdie aspekte is by die vadose sone van toepassing.

Daar is met die navorsing beoog om die kennisgaping wat tussen ingenieursgeoloë en geohidroloë bestaan te vernou. Ondersoeke in die vadose sone word deur beide ingenieursgeoloë en geohidroloë gedoen ten einde die geohidrologiese en ingenieurseienskappe van die grond te bepaal.

Die gedeelte van die geologiese profiel wat bokant die grondwatervlak voorkom, staan as die vadose sone bekend. Beide matriks- en gravitasiekragte word op die grondvog uitgeoefen. Die feit dat die hidrostatiese drukhoogte laer as atmosferiese druk is, word aan dié kragte toegeskryf ('n suigspanning word dus uitgeoefen). Die grondvog karakteristiekekurwe weerspieël die unieke verhouding tussen voginhoud en hidrostatiese drukhoogte in onversadigde gronde.

Die geometriese eienskappe van die poriekanale beïnvloed vloei in gronde. Hierdie vloei is direk proporsioneel tot die hidrouliese gradiënt en die hidrouliese konduktiwiteit. Vloei in onversadigde gronde word deur beide matriks- en gravitasiekragte beïnvloed. Die proses waarvolgens water langs voorkeurpaaie vloei staan bekend as voorkeurvloei.

Skattings van belangrike hidrogeologiese eienskappe, soos byvoorbeeld die porositeit, hidrouliese konduktiwiteit en grondvogretensie karakteristieke, kan gemaak word met behulp van geotegniese data. Skattings van die onversadigde hidrouliese konduktiwiteit kan gemaak word indien die grondvogretensie karakteristieke en versadigde hidrouliese konduktiwiteit bekend is.

Gedurende die navorsing is analises gemaak van bestaande hidrogeologiese data en laboratoriumtoetse, en veld-eksperimente is uitgevoer. Die geotegniese data is gebruik om voorspellings te maak van belangrike hidrogeologiese eienskappe. Die voorspellings is daarna vergelyk met waardes wat eksperimenteel verkry is. Die effek van voorkeurvloei en variasie van grondeienskappe is ook bestudeer.

Die porositeit, hidrouliese konduktiwiteit en grondvogretensie karakteristieke kon nie akkuraat voorspel word nie as gevolg van natuurlike variasie in geohidrologiese eienskappe en inherente foute van die impiriese modelle. Die onversadigde hidrouliese konduktiwiteit kon wel akkuraat voorspel word deur gebruik te maak van die versadigde hidrouliese konduktiwiteit en grondvogretensie karakteristieke wat eksperimenteel bepaal is.

Die studie-area, geleë te Midrand, word onderlê deur granitiese gesteentes. Die gesteentes het verskeie geomorfologiese periodes deurgemaak. Die landsisteem klassifikasiestelsel is gebruik om hidrogeologiese eenhede te bepaal. Die posisie van die hidrogeologiese eenhede ten opsigte van die topografie, geomorfologiese geskiedenis en onderliggende geologie bepaal grootliks die geohidrologiese kenmerke van die eenhede. 'n Konsepsuele model is vir elke hidrogeologiese eenheid opgestel en die belangrikheid van die eenhede, ten opsigte van grondwater aanvulling en kwesbaarheid, is bespreek.

Die navorsing het getoon dat voorspellings van geohidrologiese eienskappe met verskeie grade van akkuraatheid gemaak kan word. Voorspellings van hidrouliese konduktiwiteit, grondvogretensie karakteristieke en porositeit is nie vir gedetailleerde terrein ondersoeke geskik nie, maar kan gebruik word tydens uitvoerbaarheidsondersoeke. Waar hidrouliese konduktiwiteit en grondvogretensie karakteristieke eksperimenteel bepaal is, kan akkurate voorspellings van onversadigde hidrouliese konduktiwiteit gemaak word. Die landsisteem klassifikasiestelsel kan gebruik word om hidrogeologiese eenhede te bepaal wat gebruik kan word om grondwateraanvullings- en kwesbaarheidskaarte op te stel.

(482 woorde)

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LIST OF SYMBOLS

A	Area (m^2) [L^2], Activity of soil (-) [-]
α_w	Contact angle between water and glass (deg) [-]
C	Percentage clay content (%) [-]
C_k	Permeability change index (-) [-]
C_c	Coefficient of curvature (-) [-]
C_u	Coefficient of uniformity (-) [-]
CV	Coefficient of variability (%) [-]
d	Diameter of liquid surface curvature, depth to groundwater level (m) [L]
D	Diameter of grain (m) [L]; Fractal dimension (-) [-]
D_x	Sieve size of where x per cent of mass of soil have passed through (m) [L]
D_{10}	Effective grain diameter (m) [L]
e	Void ratio (-) [-]
ε	Porosity (-) [-]
f	fluidity (m^{-1} s^{-1}) [$L^{-1}T^{-1}$]
G	Percentage gravel content (%) [-]
g	Gravitational force (m s^{-2}) [LT^{-2}]
γ_w	Unit weight of water (N) [$ML^{-2}T^{-2}$]
h	hydraulic head (m) [L]
η	Viscosity of a fluid (kg m^{-1} s^{-1}) [$ML^{-1}T^{-1}$]
h_c	Capillary height (m) (L)
h_f	Hydraulic head at the wetting front (m) (L)
h_p	Piezometric head or Hubert's potential (m) [L]
i	Infiltration rate (m s^{-1}) [LT^{-1}]

I	Cumulative infiltration rate (m s^{-1}) [LT^{-1}]
i_c	Final infiltration rate (m s^{-1}) [LT^{-1}]
i_o	Initial infiltration rate (m s^{-1}) [LT^{-1}]
K	Hydraulic conductivity (m s^{-1}) [LT^{-1}]
k	Intrinsic hydraulic conductivity or permeability (m^2) [L^2]
K_s	Saturated hydraulic conductivity (m s^{-1}) [LT^{-1}]
K_r	Relative hydraulic conductivity (-) [-]
l	Length (m) [L]
L_f	Depth to the wetting front (m) [L]
v	Darcian velocity (m s^{-1}) [LT^{-1}]
v_s	Seepage velocity or true velocity of flow (m s^{-1}) [LT^{-1}]
M	Percentage silt content (%) [-]
N_{re}	Reynolds number (-) [-]
OM	Percentage organic matter (%) [-]
p	Pressure (Pa or N m^{-2}) [MT^{-2}L^{-1}]
ρ	Density (kg m^{-3}) [ML^{-3}]
ρ_f	Density of the fluid (kg m^{-3}) [ML^{-3}]
ρ_w	Density of water (kg m^{-3}) [ML^{-3}]
ρ_d	Dry density of soil (kg m^{-3}) [ML^{-3}]
p_0	Atmospheric pressure, by convention considered to be equal to nil (Pa or N m^{-2}) [MT^{-2}L^{-1}]
PI	Plasticity index (%) [-]
Q	Rate of flow (m^{3}s^{-1}) [L^{3}T^{-1}]
q	Specific discharge, Darcian flux or flux (cubic metre per square metre area) (m s^{-1}) [LT^{-1}]
q_{zo}	Specific discharge at groundwater surface depth (m s^{-1}) [L T^{-1}]
θ	Volumetric water content (m^3 m^{-3}) [-]
Θ	Effective degree of saturation (m^3 m^{-3}) [-]
θ_0	Initial volumetric water content (m^3 m^{-3}) [-]

θ_a	Residual air content (m^3 m^{-3}) [-]
θ_r	Residual water content or specific retention (m^3 m^{-3}) [-]
θ_s	Saturated water content (m^3 m^{-3}) [-]
Q_{tot}	Total quantity of flow over time t (m^3) [L^3]
r	Radius of the liquid surface curvature (m) [L]
R	Radius of the narrow tube or pore radius (m) [L]
ρ_d	Dry density of an undisturbed soil sample or *in situ* soil (kg m^{-3}) [ML^{-3}]
ρ_g	Density of the gas (kg m^{-3}) [ML^{-3}]
ρ_l	Density of the liquid (kg m^{-3}) [ML^{-3}]
ρ_w	Density of water (kg m^{-3}) [ML^{-3}]
r	Radius of the liquid radius curvature (m) [L]
R	Radius of the capillary/soil pore (m) [L]
RE	Recharge (m s^{-1}) [LT^{-1}]
R_{eff}	Effective pore radius (m) [L]
σ	Surface tension of a liquid (N m^{-1}) [MT^{-2}]
S	Percentage sand content (%) [-]
S_s	Specific Storage (m^{-1}) [L^{-1}]
SG	Specific gravity (-) [-]
t	Time (s) [T]
T	Temperature (°C) []
τ_s	Shearing stress (N m^{-2}) [MT^{-2}L^{-1}]
Tt	Travel time of liquids flowing through the vadose zone (s) [T]
u	Velocity (m s^{-1}) [LT^{-1}]
$\bar{u}$	Average velocity (m s^{-1}) [LT^{-1}]
u_a	Pore air pressure (Pa or N m^{-2}) [MT^{-2}L^{-1}]
u_w	Pore water pressure (Pa or N m^{-2}) [MT^{-2}L^{-1}]
V_{dz}	Deficiency zone or storage capacity of the vadose zone (m^3) [L^3]
w	Mass of sample (kg) [M]

W	Sources/Sinks discharges (cubic meter water per cubic meter soil) (s^{-1}) [T^{-1}]
ψ	Soil suction (Pa or N m^{-2}) [$MT^{-2}L^{-1}$]
ψ_b	Bubbling pressure (Pa or N m^{-2}) [$MT^{-2}L^{-1}$]
ψ_a	Air entry value (Pa or N m^{-2}) [$MT^{-2}L^{-1}$]
z	Vertical distance or depth (measured from the groundwater surface positively upwards) (m) [L]
z_0	Distance to the groundwater level (m) [L]
z_{dz}	Depth of the deficiency zone (m) [L]
z_{dz}	Depth of the deficiency zone (m) [L]