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Examining the Terzaghi Filter Pack-Aquifer Formation Relationship in Sustainable Groundwater Development in Malawi

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Abstract: Examining the Terzaghi Filter Pack-Aquifer (P-A) Formation Relationship Theory in Sustainable Groundwater Development in Malawi.

In Malawi, boreholes have a non-functionality rate of about 30%. Non-functionality due to incongruent properties of filter pack and aquifer formation, according to the theory developed by Terzaghi which states

$$\frac{d_{15}(filter)}{d_{85}(formation)} < 4 < \frac{d_{15}(filter)}{d_{15}(formation)}$$

has not been explored. This study examined the extent to which the Terzaghi P-A Relationship Theory is applied in sustainable groundwater development in Malawi.

Fifty three aquifers were sampled. Filter pack samples were collected from Mangochi and Karonga. Grading and analyses to BS 1377 Part 2: 1990 were done. Terzaghi Migration (T_m), Terzaghi Permeability, (T_p) factors and filter pack Uniformity Coefficient, C_{uF}, were deduced. T_m and T_p were checked against Terzaghi theory. C_{uF} was checked against The Code of Practice (CoP) for Borehole Drilling in Malawi which limits $C_{uF} \leq 2$ and $D_{50F} \leq 1$. Borehole drilling, design and construction were observed to relate theory to practice.

There was 100% compliance on T_p and 87% on T_m. Nineteen percent of the samples had P-A ratios between 4 and 10, $C_{uF} > 2$, and $D_{50F} > 1$. Malawi's filter pack, from source, is not compatible with the aquifer formation properties. Consistency with either the Terzaghi criteria or CoP for borehole drilling is not clear. No filter park selection is done.

Key words: Aquifer Formation, Boreholes, Filter Pack, Non-functionality, Terzaghi Theory

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1. Introduction

Background

In 1921, while working on earthen dams, Terzaghi introduced a granular fill at the base of the dam whose gradation would retain the fine materials while passing the seepage (Terzaghi, 1941). The granular fill gradation was dependent on the base material. In water well construction like boreholes, a filter pack is introduced between the hole annulus and the casings (Moss Roscoe, 1990). The filter pack retains the fine materials while passing the seepage. The filter pack stabilizes the aquifer too (Harich, 2009). The property of the filter pack is dependent on the aquifer formation material properties. Just like a mismatch in the properties of the granular fill and the base material would lead to eventual failure of a dam, a mismatch in the filter pack-aquifer properties would affect performance of a borehole in the medium and long term.

Terzhagi concluded that the filter material should be above 400 % larger the gradation size of the formation. This is the same operating principle in boreholes as observed by Roscoe Moss Company. The Standard Operating Procedures[1] (SOPs) (Aurecon, 2012) for borehole drilling in Malawi acknowledges the need for filter pack in the borehole construction. The SOP further observes that the filter gradation should not be above 1 mm using the d_{50} sieve so that fines do not get into the borehole through the slotted casings. Globally, the operating principle of water wells like boreholes borrow from the theory developed by Terzhagi. Whether the filter pack as outlined in the SOPs in Malawi is according to the theory as described above is the issue that needs to be ascertained.

The world is on the verge of water crisis; over one billion people lack access to an adequate water supply (WHO/UNICEF, 2006). While the 2013 Mellenium Development Goals report registers 2.1 billion people gaining access to improved drinking water sources since 1990, and thus exceeding the MDG target, access to drinking water for the rural poor, along with water quality and safety remain serious concerns. The report observes that 768 million people still drew water from unimproved source in 2011 (UN, 2013). Eighty three percent of this population is rural.

The 2025 Africa Water Vision also records that in the SADC region, water demand is expected to rise by at least 3% annually until 2020, a rate equal to the regional population growth; this is as quoted from the 1994 SADC report. (Water/Africa, 2008)

[1] SOPs for drilling and construction of National Monitoring boreholes in Malawi

In his blog, Professor Richard Carter, Chair of Rural Water Supply Network, quotes the 2012 update of the Joint Monitoring Program's Progress on Drinking Water and Sanitation that about One billion people in rural areas rely on boreholes for their water supply including another 300 million in small towns and cities.

In Malawi, 80% of the population lives in rural areas[2] (NSO, 2008). In line with target 10 of the Millennium Development Goals[3] (MDG), the Malawi Growth and Development Strategy, MGDS, seeks to improve access to clean water and sanitation. Malawi intends to increase access to clean water within 500 meters walking distance for all people, and thereby ensuring that basic water requirements of every Malawian are met while the natural ecosystem is enhanced[4]. Climate change is continually posing a threat to surface water availability. Most rivers in Malawi have become annual. There is no surface water flow in dry season. Yet groundwater is accessed through deep boreholes in the same time period and vicinity. Groundwater therefore remains a feasible option in the near term (Bonsor, 2010). Bonsor, MacDonald and Calow observes that "unlike surface water, groundwater[5] is less responsive to short term climatic variability and will be buffered to the effects of climate change in the near –term as a result of the storage capacity of the aquifer".

Water supply to rural areas of Malawi is largely through boreholes. In order to sustainably meet the 2015 MDG target, and also respond to the MDGS II priority in water supply and sanitation, the boreholes being constructed now must be so constructed as to be sustainable[6] enough in order to meet the current and future demands in the wake of the effects of climate change. Yet supply of water is intermittent and not reliable (ADB, 2012). Non-functionality due to incongruent properties of the filter pack and aquifer formation, according to the theory developed by Terzhagi in 1921, has not been explored in the Malawian context.

Borehole construction for sustainable water supply calls for many steps and procedures. Each of these steps may not be superior to the other but complement each other towards attaining a sustainable product in water supply.

One of the procedures in borehole construction is the filling in of filter pack between the casings and the borehole annulus. The Standard Operating Procedures for Borehole construction in Malawi calls for filter pack installation for all boreholes. This procedure is necessary. Filter pack must be so designed as to relate to the aquifer formation. A common consensus is that a filter pack will normally perform well if the uniformity coefficient is similar to that of the aquifer[7] (Moss Roscoe, 1990). The SOP for Malawi limits the uniformity coefficient to 2. This theory (the Terzhagi theory) seeks to ensure that the designed filter pack does not allow

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[2] This is according to the 2008 Population and Housing Census
[3] Target 10 seeks to increase sustainable access to safe water
[4] The MDGS has been aligned to the Millennium Development Goals MDGs which seeks to half the population with access to safe and portable water supply by 2015
[5] This refers to improved sources such as boreholes (generally 20 meters below ground surface) equipped with hand pumps
[6] Sustainability looks at the ability of a service to provide a reliable and adequate water supply in the long term
[7] This is according to the theory developed by Terzhagi in 1943

fines from the aquifer formation to pass through it and clog the casing slots and eventually choke the borehole capacity[8].

Estimates by the Rural Water Supply Network (RWSN), records that up to a third of the water points in Sub-Saharan Africa are out of service at any given time as shown below

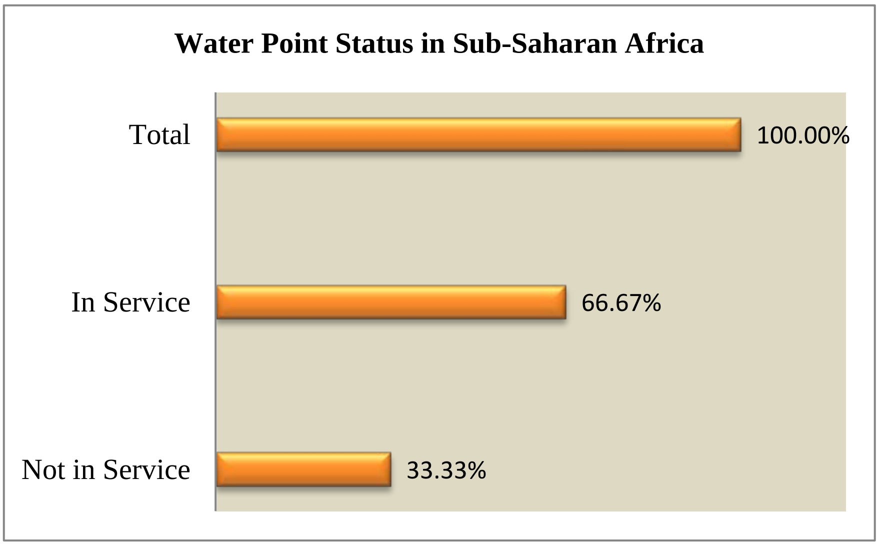

Figure 1: Water point status in Sub-Saharan Africa

Government of Malawi records that 35,000 boreholes have been drilled with a non-functionality rate of about 30%[9]. This non-functionality is due to several problems; hydrogeological, (to do with aquifer parameters), unreliable borehole citing, design and construction which can lead to premature failure. The third reason is attributable to human management, demand and monetary challenges. It is not easy to adequately define a problem that is underground as the case with boreholes. (Casey, 2014).

The 2012 Joint Sector Review (JSR) Report observes that while the MDG on water was met in 2007, access in rural communities has not been improving over the years (WHO/UNICEF, 2012). There are observed functionality problems. The report further alludes to declining yields at water sources as accounting for some of the low figures in functionality. Why does borehole yield decline? Furthermore, the infrastructure is either dilapidated and has low efficiency generally (ADB, 2012). A lot has been attributed to the non-functionality of these borehole water points as noted above. Khaled and Abduljawad (Khaled A. R., 2013) in their presentation "A Guide to Designing Water Wells" quotes Driscoll, 1986 on water well design " to produce a combination of longevity, performance and cost effectiveness, a proper design reduces the risk of well failure, and thereby

[8] If the slots are chocked, water flow into the borehole casing is inhibited; reducing the yield and threatening borehole sustainability
[9] Ministry of Water Development and Irrigation, 2013

provides greater assurance that the well will satisfy the intended purpose". Identifying aquifer type and determining screen and filter characteristics are but a few of the many steps in well design. The filter pack provides an annular zone with high permeability, and thus increasing the effective radius and yield of the well.

The challenges in borehole non functionality need to be investigated better to determine whether yields can be improved and water points are made sustainable. In Malawi, it is not uncommon to have boreholes that yield well when they have just been commissioned. The yield then reduces over time and will pick up again after redevelopment[10]. The question that can be raised here is: what is the cause of this inconsistency of the yield is over time and how can it be solved?

The Standard Operating Procedures for drilling boreholes in Malawi demand use of filter pack in borehole construction (GoM, 2008). In Malawi there are two approved sites by Government's Ministry of Agriculture, Irrigation and Water Development (MoAIWD) where drillers can collect filter pack. These are Nkhuzi Bay in Mangochi and Chilumba in Karonga. Application of filter pack is a key component in borehole construction in Malawi!

The 2007 Integrated Water Resources Management Plan (IWRMP) for Malawi acknowledges that groundwater resources in Malawi occur mainly in two aquifer types; the weathered basement complex and the alluvial aquifers (GoM, 2007). These two aquifers have different formation properties. The alluvial ones are fluvial and lucastrine and vary in both lateral sequence and extent. The question now is how compatible the filter pack from Nkhuzi Bay and Chilumba is to the varying aquifer formations across Malawi with respect to the Terzaghi theory.

This research sought to examine the Terzaghi filter pack-aquifer formation relationship theory in sustainable ground water development in Malawi with the following specific objectives;

1) Deduce whether the aquifer formation/filter pack properties meet the Terzaghi criteria;
2) Analyze Malawi's filter pack/aquifer formation ratios and uniformity coefficient; and
3) Present the current borehole construction practices on formation sampling and filter pack gradation.

A filter pack that relates well with the aquifer formation is a recipe for sustainable groundwater development. Knowledge of this relationship will aid in informed borehole construction; using a proper filter pack according to the aquifer formation encountered. Water is life. Access to safe water is a human right. Access to water must therefore never be compromised by irrational practices. The efforts Malawi is making in meeting the MDG target in water supply must be sustained. Filter pack installation ought to be done rationally for sustainable groundwater development. This research work sought to check this.

[10] This is a functionality issue

According to the Government of Malawi Technical Manual on Water Wells, assessment of Malawi's borehole capacities is yet to be concluded. At the moment 29 monitoring wells exist; (the number has been expected to get to 100 or more, covering different aquifer units) (GoM, 2008). Thus not all aquifers in Malawi are characterized. This study can help inform the approach in the drilling of the other monitoring wells**.**

2. Methodology

Hypothesis

a) Alternate hypothesis

An appropriate filter pack enhances the performance of a borehole water point.

b) Null hypothesis

An appropriate filter pack cannot significantly enhance performance of a borehole water point.

The theory to be tested was developed by Terzaghi in 1921 and involves the relationship between the filter (gravel pack) and aquifer formation material. The theory, as quoted by Roscoe Moss Company states $\frac{d_{15}\ (filter)}{d_{85}\ (formation)} < 4 < \frac{d_{15}\ (filter)}{d_{15}\ (formation)}$ (Moss, Roscoe, 1990); thus the filter material should be larger than four times the gradation size of the formation. Fifteen percent of the filter material should be smaller than four times the coarsest 15% of the formation. This theory was meant to introduce a granular base in a dam whose gradation would retain the fine materials while passing the seepage. This is the same operating principle in water wells like boreholes.

Does this theory apply in the Malawian context?

Research Approach and Design

This research work is mainly quantitative where research variables, filter pack and aquifer formation, are measured numerically and later analyzed

The driving philosophy for this research work is positivism. According to Saunders, this philosophy adopts the stance of the natural scientist. Under this philosophy, data is collected about an observable reality and search for regularities and causal relationship.

An existing theory was used to develop hypotheses which were later to be confirmed wholly or partially. Facts as opposed to impressions were used.

The approach was deductive using data measured numerically to test the theory. Relationships between variables were examined. All data was derived through experiments.

In this research, the aquifer formation material is the independent variable while the filter pack is the dependent variable.

Sample Design

Purposive/Judgmental Sampling was used to select cases that would best answer the research questions while at the same time meeting the objectives of the research. It has been noted that Malawi has different hydrogeological units scattered across the country, 70% of which is composed of basement aquifers. In order to be able to cover as much of these units as possible, sampling was deliberately tackled purposively.

In order to get the aquifer samples, drilling is involved. Drilling is an expensive exercise. For this reason, a network with drilling companies and client organizations was developed, World Vision International in this case. This assisted in deciding when and where to collect samples, and this was largely influenced by the available financial resources. Sampling started in May 2014 and was completed in December 2014. A total of 50 aquifer formation and 3 filter pack samples were collected.

Data Collection

Data collection was done from May to December 2014. Fifty aquifer formation samples were collected from Balaka, Neno, Ntchisi, Kasungu and Karonga districts. These districts were purposively selected as they cover almost all aquifer types present in Malawi. Filter pack samples were collected from government approved sites of Chilumba in Karonga, Nkhuzi Bay in Mangochi. Another sample was collected from Senga bay in Salima to appreciate why government does not approve filter pack from this site despite drillers using the same for boreholes in central region of Malawi. The collected samples were sent to the Ministry of Transport and Public Infrastructure (MoTPI) materials laboratory for grading analysis. Grading was done using standard methods according to BS 1377: Part 2. Results obtained from the grading tests were plotted on graphs. The graphs were then analyzed.

Data Analysis

Grading was according to BS 1377: Part 2 1990. This is the acceptable standard of materials grading by the MoTPI. This was carried out at the Ministry's Central Materials Laboratory in Lilongwe. Results were presented graphically and conclusions drawn based on the observed and recorded results of the grading tests with reference to the equation shown below: (The Terzaghi Filter Pack-Aquifer formation relationship)

$$\frac{d_{15}\ (filter)}{d_{85}\ (formation)} < 4 < \frac{d_{15}\ (filter)}{d_{15}\ (formation)}$$

From the graphs plotted, important parameters of concern were deduced. These parameters, annotated thus d_p where d represents sieve size in millimeter and the subscript represents percentage passing. Of interest on this research were the following:

- $d_{10,}$ (Particle grain size diameter at 10% passing)
- d_{15} (Particle grain size diameter at 15% passing)
- d_{50} (Particle grain size diameter at 50% passing)
- d_{60} (Particle grain size diameter at 60% passing)
- d_{85} (Particle grain size diameter at 85% passing)

In order to define the sample being analyzed an additional notation was used. In this case:
$d_{p\ (filter)}$ depicts that the sample is filter pack, while $d_{p\ (formation)}$ stands for aquifer formation.

Analyses of these samples followed the standard procedures for analyzing soils based on BS 1377: Part 2, 1990 and according to the design criteria and theory being tested.

3. Results and Discussion

Introduction

A total of 53 samples were purposively collected across Malawi, covering almost all aquifer types and filter pack sites present in Malawi.

Filter pack samples were collected from all the approved sites; Nkhuzi Bay in Mangochi and Chilumba in Karonga. Another sample was collected from Senga Bay in Salima. The researcher observed that drillers still collect filter pack from this site for borehole construction.

All collected samples went through grading analysis to determine particle size distribution. Grading was done according to BS 1377 Part 2; 1990. Graphs showing percentage passing by weight on the linear vertical scale against particle size diameter on the horizontal logarithmic scale were plotted. Key aquifer and filter pack parameters were deduced. The deduced parameters informed the analysis of the results.

Presentation outline

The theory being analyzed will first be introduced and explained. Results will be presented thematically following the specific objectives the research seeks to address. The research questions will also be addressed simultaneously.

Terzaghi Criteria

The relationship below was examined. In this relationship:

$$\frac{d_{15}(filter)}{d_{85}(formation)} < 4 < \frac{d_{15}(filter)}{d_{15}(formation)}$$

- Characteristic particle size of filter pack must exceed that of formation to increase filter permeability.
- The ratio between the characteristic filter size to the finer segment of the formation should not be too large to avoid formation material migrating through the pack thereby reducing permeability (Roscoe Moss, 1990).
- The left hand side of the relationship is called the Terzaghi Migration factor (T_m). This factor (T_m) checks erosion of core material that may result in sinkholes, weakening and dislocation of fill material (Terzaghi, 1941). From this relationship $Tm \leq 4$.
- The right hand side represents the Terzaghi Permeability factor, (T_p). Formation and aquifer permeability are crucial to sustainable boreholes in terms of maintaining the yield. T_p must be ≥ 4.

Aquifer Parameters

Table 1: Filter pack parameters

ID	Source	Parameters				
		D_{15F}	D_{50F}	D_{60F}	D_{10F}	$C_{uF=} D_{60F}/D_{10F}$
#1	Senga Bay	1.180	3.150	3.750	0.700	5.357
#2	Nkope/Nkhuzi bay	1.180	2.750	3.000	1.000	3.000
#3	Chilumba	1.500	2.650	3.000	1.180	2.542

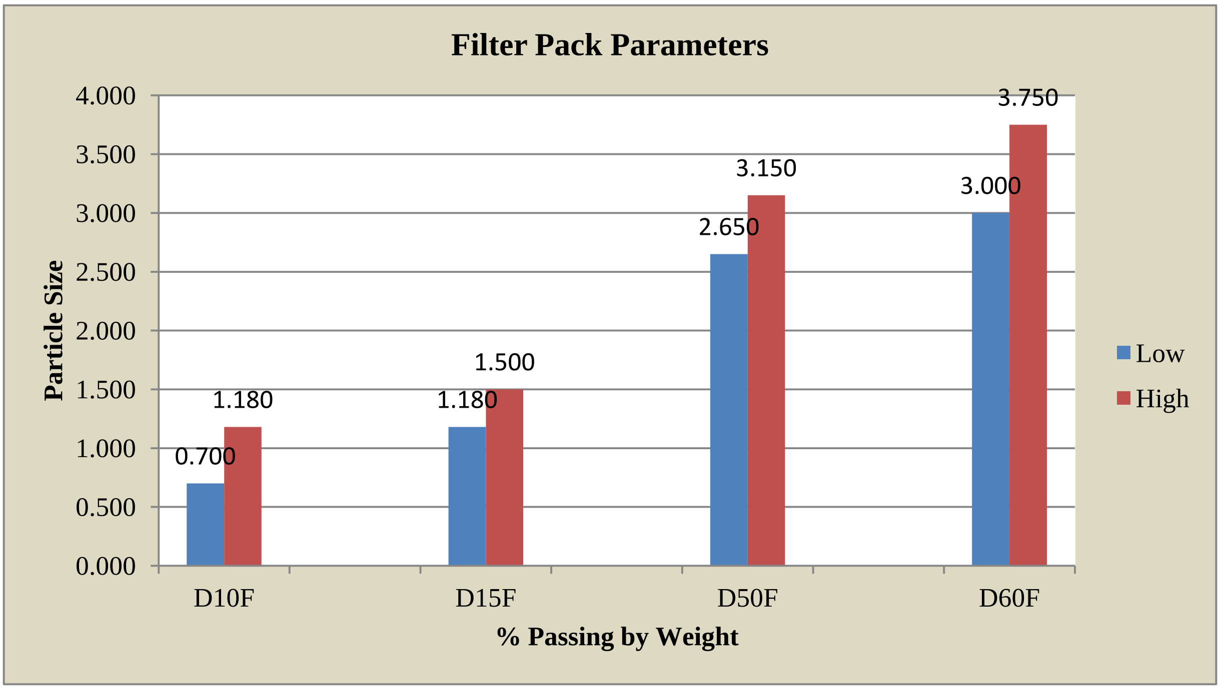

Figure 2: Filter pack parameters

Senga -Bay filter pack has the highest uniformity coefficient indicating a high particle size range.

The Code of Practice (CoP) for Borehole Drilling in Malawi stipulates a filter pack Uniformity Coefficient of **≤ 2**

Although **Nkhuzi- Bay** and **Chilumba** filter pack have smaller C_u, none of them meet the **CoP criteria of ≤ 2**

- The Code of Practice for Borehole Construction demands that $D_{50F} \leq 1$ for boreholes equipped with hand pumps, (Cl.10.1MS 532:1999). All filter packs sampled have $D_{50F} > 1$
- Cl. 10.4 observes that filter pack size for all boreholes to be equipped with motorized pumps must be informed by gradation curves of the aquifer material
- To deduce T_m and T_p ratios, the D of the filter is compared with the D of the aquifer i.e. D_{15f}/D_{85a} for T_m and D_{15f}/D_{15a} for T_p.

Aquifer parameters of all boreholes sampled are shown below.

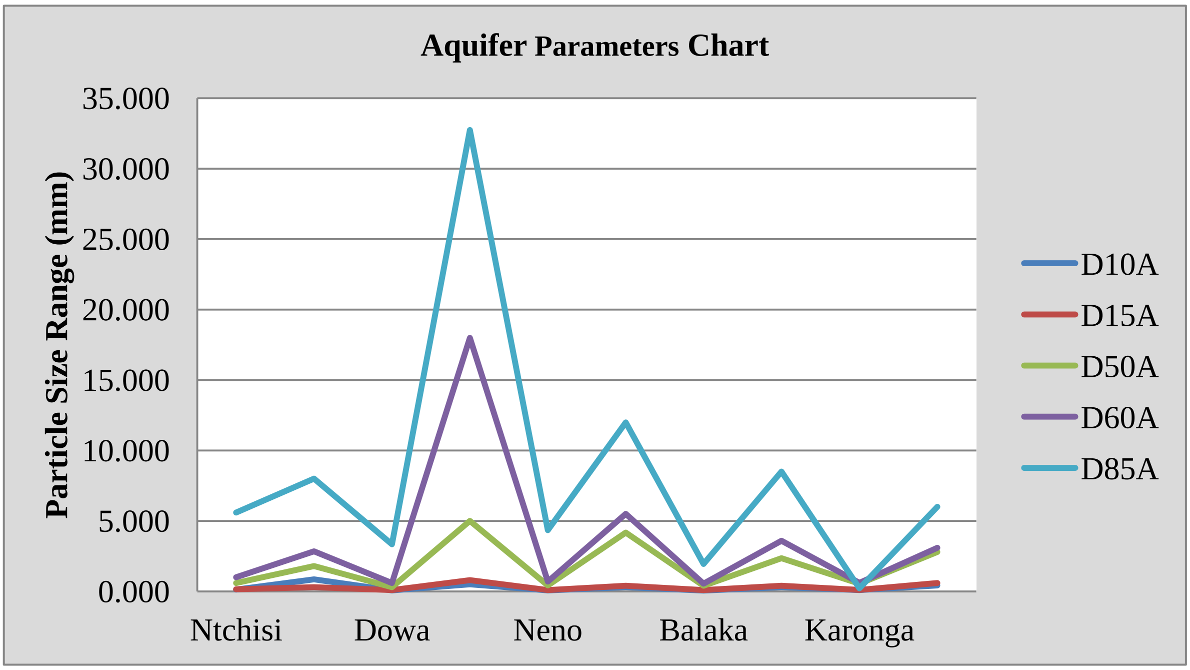

Figure 3: Aquifer parameters

Balaka has 0.060mm, being smallest of all at $D_{10.}$

Dowa registered least particle size diameter for D_{15}, D_{50} and D_{60} at 0.093mm, 0.300mm and 0.600mm respectively.

The smallest particle size is the most critical and filter pack design must be based on these.

With D_{85} at 0.220mm, Karonga has the least particle size

Terzaghi Factors

Considering only the most critical particle grain size diameter, a range of Terzaghi factors were deduced and presented below;

Table 2: Terzaghi factors

District	T_m			T_p		
	Nkhuzi Bay	**Chilumba**	**Senga Bay**	**Nkhuzi Bay**	**Chilumba**	**Senga Bay**
Karonga	5.364	6.091	5.364	10.727	12.182	10.727
Dowa	0.352	0.4	0.352	12.688	14.409	12.688
Balaka	0.605	0.687	0.605	13.111	14.889	13.111
Ntchisi	0.211	0.239	0.211	9.44	10.72	9.44
Neno	0.271	0.308	0.271	11.8	13.4	11.800

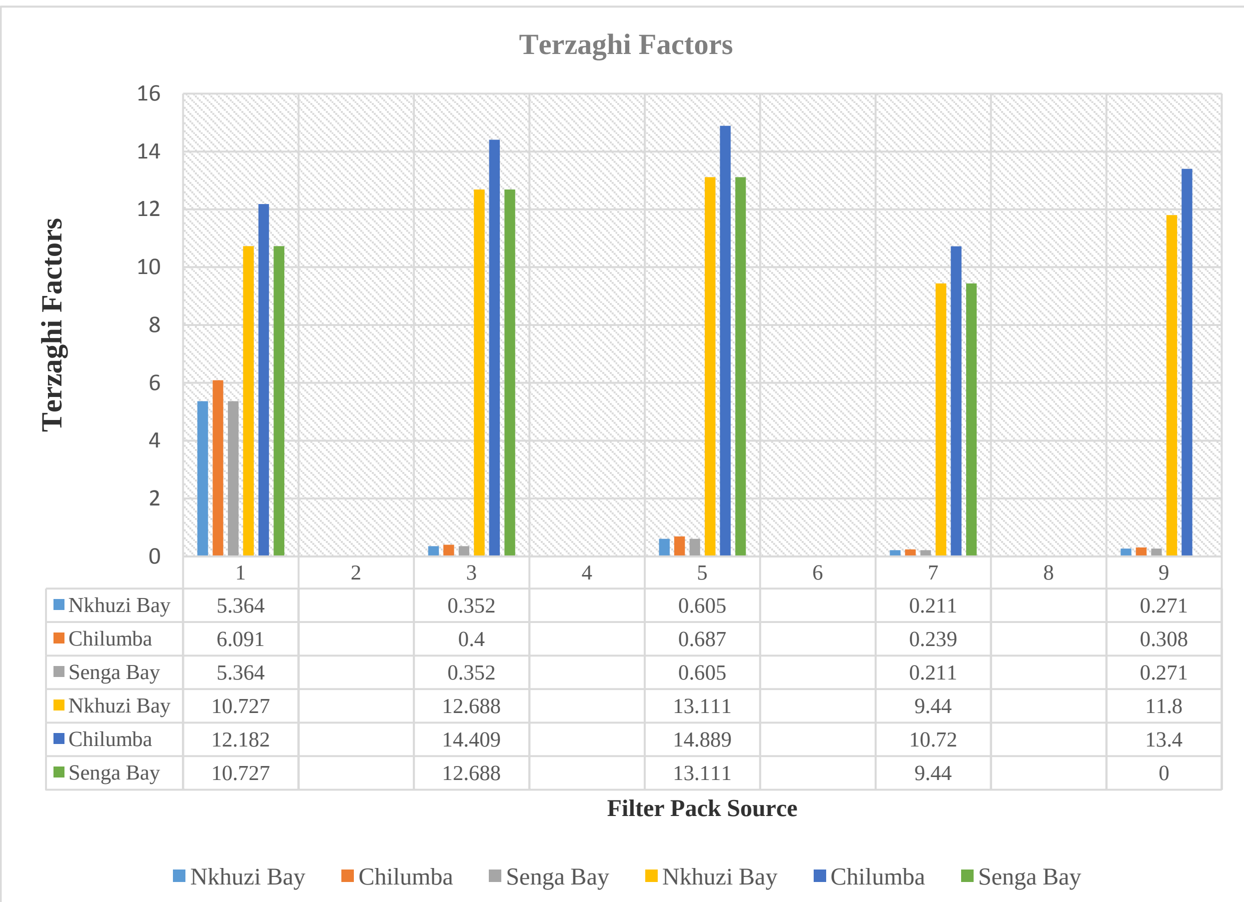

Figure 4: Terzaghi factors

According to Tezaghi, $T_p \geq 4$ and $T_m \leq 4$

In these samples, 100% has $T_p \geq 4$ in Neno, Ntchisi, Balaka and Dowa and Karonga.

$T_m \leq 4$. Except Karonga, this criterion is met in Neno, Ntchisi, Balaka and Dowa, representing 87%.

These factors can sometimes be influenced by the presence of clay. Clay is problematic as it cannot be fully pulverized during drilling. Expert knowledge of the area and knowledge of how to analyze grading results before using them is crucial to selecting filter pack material. *(Turnbull, Technical Memorandum 012-5.)*

4. **Results based on Specific Objectives**

Deduce whether the filter pack/aquifer formation properties meet the Terzhagi criteria.

- From the above discussion, the existing filter pack/aquifer formation material, met 100% on Terzaghi criteria on permeability while 87% responded positively to migration factor;
- Thirteen percent failure on migration factor could cause the aquifer formation material to migrate through the filter pore spaces which can eventually affect permeability of the filter. The finest sediments are the ones that cause problems when pumping (Turnbull, Technical Memorandum 010-3:)
- According to Terzaghi, the grain size of the aquifer material has to be multiplied by a factor of 4-6 in order to come up with an allied, compatible filter pack.
- Filter pack is a product of weathering which itself is influenced by several dynamics of the parameters at work. Filter pack properties, especially those related to grain size diameter, are bound to change in response to this dynamism.
- It is not surprising the filter pack/aquifer formation properties, in the filter packs natural state are not wholly consistent with the Terzaghi criteria. The filter pack, being a variable that can be manipulated must be worked on to conform to the criteria in question.

Analyze Malawi's filter Pack-Aquifer (P/A) ratios

- P/A ratio is defined as ratio of 50-percent size of filter pack to the 50-percent size of aquifer material
- Below, Figure 5, is the range of the sampled aquifers.

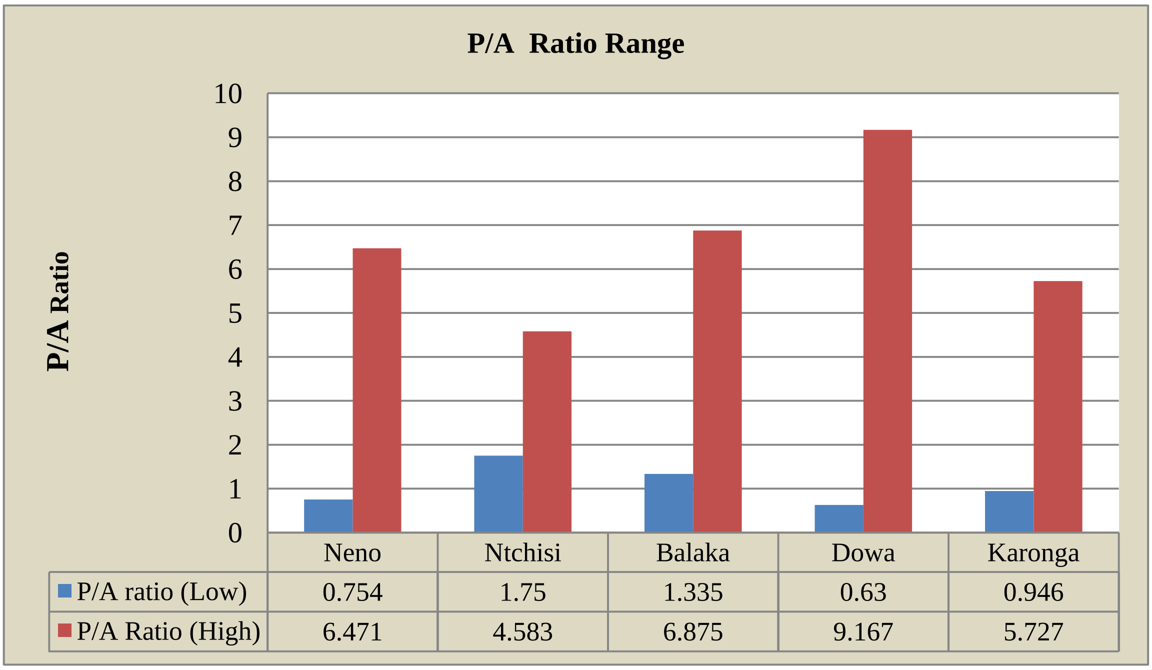

Figure 5: Pack-Aquifer ratios

P/A ranges 0.63<P/A<9.67

P/A acceptable range according to Terzaghi 4<P/A<10

19% of all samples have 4< P/A<10

Wells with smaller or larger ratios have less efficiency (Smith, 1954).

Malawi's filter pack, being a dependent variable, needs to be worked on to match with the formation properties for better results. The selection of the filter pack must be based on the most critical grain size of the aquifer material i.e. the smallest grain size.

Current borehole construction practices on formation sampling and filter pack gradation

Introduction

Malawi has in place a Code of Practice (CoP) for Borehole Drilling. This CoP is the main standard for the borehole drilling in Malawi and the Malawi Bureau of Standards identifies it as MS 532:1999. The CoP is consistent with the Terzaghi criteria of having a systematic approach to filter pack selection.

All borehole-drilling for ground water development in Malawi is regulated by the MoAIWD. Several players, both governmental and non-governmental organizations, are involved in drilling boreholes for water supply for both domestic and non-domestic uses. District water officers, where available, do inspect the process of borehole drilling and construction and sign off the drilling reports.

The proceeding is based on observations at actual borehole drilling and construction site, as captured below; Figure 6.

Figure 6: Drilling in Ntchisi

Borehole Drilling In Practice

Soil Samples were collected at every meter of drilling depth all the way to the final depth. In practice, these samples inform the drillers where the water bearing formation is met (water strike). These positions help in borehole design: determining the position for slotted and plain casings. The slotted casings allow water entry into the casings. Plain ones retain the water within and provide a reservoir for pumping purposes. Placement of casings is followed by filter pack application. The filter pack is placed onto the well annulus in its natural state, (as it came from the source). In all these operations, the District Water Officer, where available, is on site, as an inspector for government. The figure below shows the drillers log/lithology log at a typical drilling site in Ntchisi district. Only water bearing (aquifer) formation samples are collected for grading tests.

Figure 7: Aquifer sampling

5. Conclusion

The preceding discussion establishes the following key points as conclusion:

(a) In its natural state, Malawi's filter pack, regardless of its source, is not wholly compatible with the aquifer formation properties. These two variables are not wholly consistent with the Terzaghi criteria, as they are. The Filter Pack can be manipulated to meet the properties of the aquifer encountered. The filter pack selection must be based on the effective particle grain size diameter of the aquifer formation material. Furthermore, the CoP use of $D_{50F} \leq 1$ and $C_{uf} \leq 2$ is not consistent with the available filter pack at the moment. Actual $D_{50F} > 1$. Filter pack from Chilumba and Nkhuzi Bay is slightly above 2, and therefore uniformly graded. The filter pack from Senga Bay has a larger uniformity coefficient of > 5. This filter is well graded and non-uniform. No wonder this filter pack is not recommended by the ministry.

(b) The P/A ratios for the boreholes sampled show that no single filter pack, in its natural state, is suitable for any of the aquifer formations sampled.

(c) There is no rationality in the selection of filter pack in practice. Filter pack is applied without regard to the formation properties encountered. While there is a CoP for borehole drilling in Malawi, and a guide to recommended filter pack collection points, the practice on the ground does not follow any of this as regards filter pack collection, selection and design. In fact, there is no filter pack design employed at all; No gradation is done for filter pack, whether for boreholes to be equipped with hand pumps or those to be equipped with motorized pumps. It is interesting to note that even government drilling team collects filter pack from Senga Bay for boreholes drilled in Central region.

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