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Sedimentation tank design for rural communities in the hilly regions of Nepal

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Abstract

Mathillo Semrang in rural Nepal relies on stream sources to provide drinking water. Erosion and deforestation of local terrain produces turbid water that requires treatment before distribution. The current round gravity sedimentation technology is large in footprint and cannot handle large water flow-rates and silt concentrations resulting from extreme weather events. In partnership with Nepal Water for Health (NEWAH) and Engineers Without Borders Australia (EWB), the project aim was the design of a small footprint inclined plate settler (IPS) to treat influent flow-rates ranging from 0.25 to 4 L/s. A 76% decrease in footprint was achieved by the IPS design for source flow-rates up to 4 L/s. Laboratory analysis revealed the optimum flow-rate of operation is approximately 10% of the maximum design flow-rate (4 L/s). Further research is needed to establish this finding along with further collaboration with rural Nepalese communities and NEWAH.

Keywords

sedimentation, clarification, Stokes' Theory, Inclined Plate Settlers

Introduction

Drinking Water in Thumi VDC – Nepal

Nepal ranks among the top nations in terms of fresh water potential Water Resources Management Committee, 2010). The secure provision and distribution of drinking water is crucial in boosting socio-economical development and increasing standards of living, but little has been done thus far at a government level to ensure this outcome. In rural areas, the majority of the inhabitants do not have access to safe drinking water. One such rural village is Mathillo Semrang in the Thumi Village Development Community (VDC) in the Western Region of Nepal.

Drinking water in Mathillo Semrang is sourced from hill and mountain springs that are subject to high sediment loads, particularly during monsoon and landslide events. Large concentrations of fine sediment in suspension results in high turbidity water sources. Mountainous terrain deforestation and land degradation are key contributors to high sediment inflows (Julien & Shah, 2005).

Nepal Water for Health (NEWAH) is the national Nepalese non-government organisation established in 1992 to address the water and sanitation (WASH) needs of the rural communities of Nepal (Nepal Water for Health, 2011). Many NEWAH WASH programs involve the upgrade or installation of water supply systems from source to tap. In the hilly regions of the Western region of Nepal, where sources are turbid, NEWAH and local workers install sedimentation facilities prior to the distribution of water to villages. Traditionally these sedimentation facilities have consisted of round sedimentation tanks employing gravity sedimentation. However, it has been identified by NEWAH that in many cases there is insufficient space for the existing technology.

The aim was to design a small footprint, high rate sedimentation system to treat the turbidity issues arising from stream sources in rural hilly regions of Nepal. The new design must meet the following criteria:

1. It must have the potential to produce water of equal or greater quality than that currently produced by the existing technology.
2. It must be low in cost with respect to both construction and operation.
3. It must be easily implemented on steep gradients.
4. It must be stable enough to withstand extreme weather conditions, i.e. monsoonal rainfall and land slides.
5. It must be small enough to suit the Nepalese water supply system.
6. It must require minimal or no machinery to construct and no electricity to operate.

Description of Current Design

The current sedimentation system employed in Mathillo Semrang is the round “Ferrocement Water Filter” tank (Appendix 1). It is a round clarification device with a rectangular valve box attached to the rear of the device. The tank itself is doughnut in shape containing two settling basins. The influent water enters the first central basin where it is allowed to settle. The settled particles collect at the base of the vessel via a sloping floor. The clarified effluent in the central basin then enters the outer basin through a transfer pipe. This water travels in a clockwise direction to settle; the clockwise movement of the water reduces the potential for short-circuiting in the system. The clarified effluent in this outer basin leaves the system through the outlet pipe and travels straight to distribution.

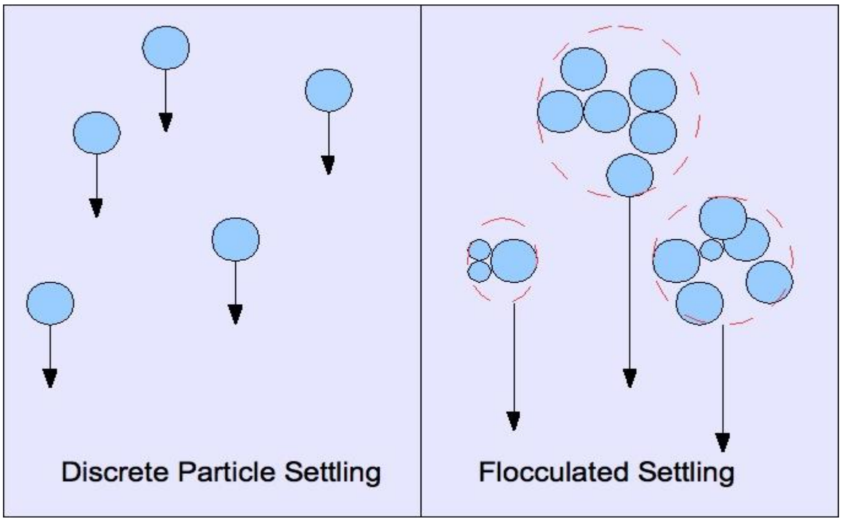
The settled particles are removed from the system via a “washout cycle”. This involves entering the valve box via a manhole. The valve servicing the outlet pipe is closed and the washout pipes are opened. The normal operation of the system then allows the accumulated settled particles to be flushed from the system.

Fundamental Design Principles of Sedimentation Units

The design of the current system is based on the principle of gravity settling. Gravity settling occurs in tanks of water with large cross-sectional areas where small influent and outward flows create a state of virtual quiescence in the system. Under the influence of gravity, particles with densities higher than that of the surrounding fluid will sink (sedimentation) whilst lighter particles will travel upwards or float (flotation) (Huisman, 1986). The particles present in the system are retained in the sludge layer at the bottom of the tank. This allows the water to leave the system in a clarified state (Huisman, 1986).

The rate of rise or fall of the particles depends on the particle size and particle density relative to the fluid. Larger particles descend more rapidly than smaller particles. The size of particle can be changed by aggregation. This segregates the types of clarification experienced in settling into two types (Figure 1): discrete settling and flocculated settling.

Figure 1: Schematic showing difference between discrete and flocculated settling



Discrete settling occurs in systems with small particle concentrations where particle aggregation is negligible and settling occurs by natural forces (i.e. gravity). In discrete settling, the terminal velocity or settling rate of the particles can be calculated using Stokes' law (Equation 1) which assumes the rate depends only on the size of the particle, shape (sphericity) and density as well as the viscosity and density of the surrounding fluid. Stokes' law is:

$$U_t = S_o = \frac{d^2 \times g \times (\rho - \rho_f)}{18 \times \mu} \quad (1)$$

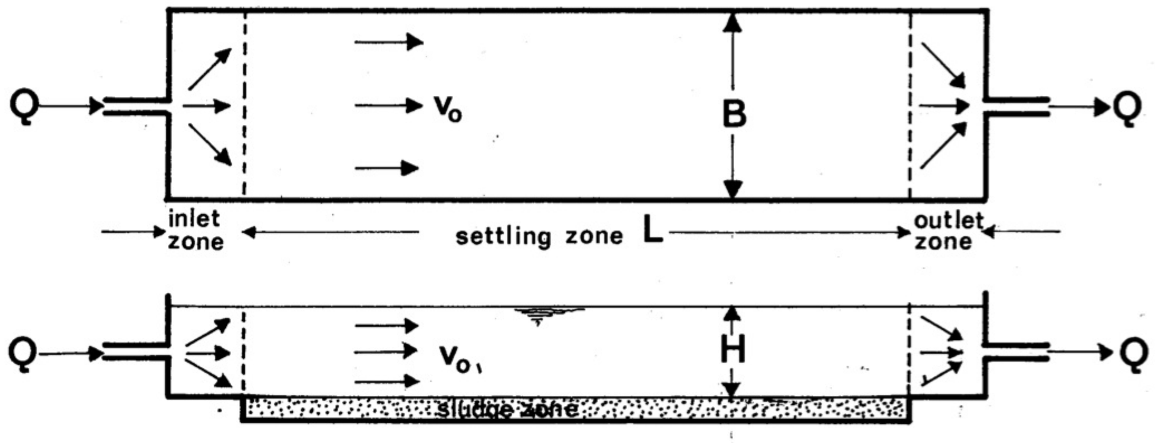
where, *d* is the particle diameter, *g* is the gravitational acceleration constant (m^2/s), μ is the fluid viscosity (Ns/m^2), ρ is the particle density (kg/m^3), ρ_f is the fluid density (kg/m^3), U_t is the terminal velocity of particle (m/s) and S_o is the Stokes' settling rate of particle (m/s).

The overflow parameter is the crucial parameter in the design. It is typically expressed as a rate of flow per unit area (m^3/m^2 time) (Demir, 1995) and is generally chosen to be half of the value of the Stokes' settling rate. For a fixed influent rate, adequate particle removal only depends on the surface area of the tank (Demir, 1995).

For low removal ratios, a slight increase in tank area results in a large improvement in particle removal, however if large removal ratios are required, large increases in tank cross sectional area are also required (Camp, 1946)*;* this is inconvenient in cases where land availability is small.

Sedimentation tanks are typically rectangular, square or circular and water flow occurs in a continuous manner either in a horizontal or vertical horizontal direction. The typical design of the a sedimentation tank involves four major components (Figure 2)(Huisman, 1986):

Figure 2: Horizontal flow sedimentation tank showing the four typical zones in construction. Image source: (Huisman, 1989)

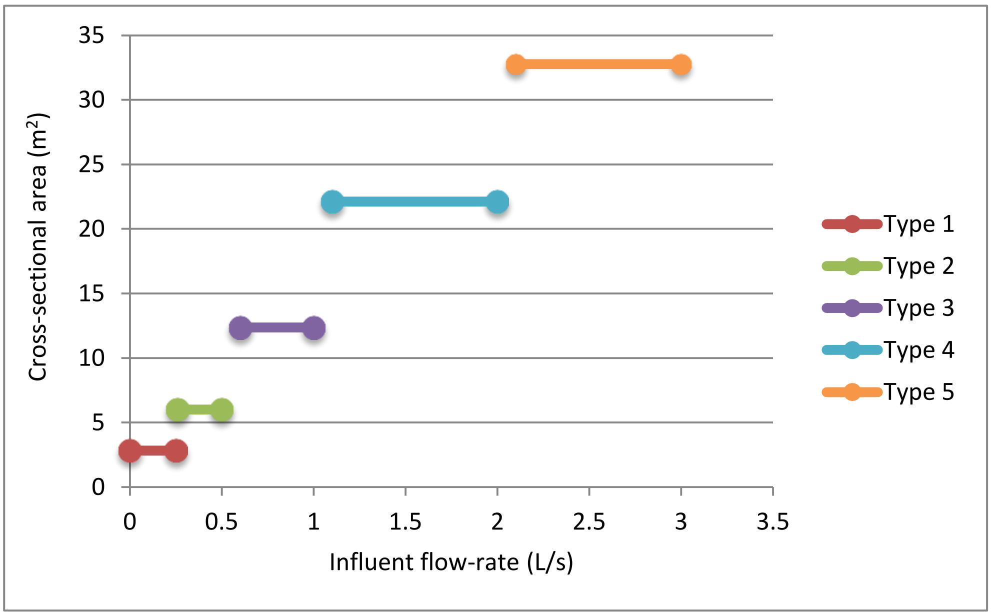


1. The **inlet zone** allows the uniform dispersion of the influent into the tank over the entire cross-sectional area.
2. The **settling zone** where the suspended particles subside through the flowing water.
3. The **sludge zone** in which the removed particles accumulate and from which they are removed for disposal.
4. **Outlet construction** that collects the clarified liquid uniformly over the cross-sectional area of the tank.

Current Tank Design

Figure 3 provides the operational range of the five Ferrocement water filter tanks currently in use. These designs vary in cross-sectional area to suit the influent flow rate to the system. The design parameters are calculated using Stokes' law on the basis of a 10 micron silt particle.

Figure 3: Tank cross-sectional area varying by type for different influent flows.



The tank types cover flow ranges from 0.25 L/s to 3 L/s. Influent flow-rates greater than 3 L/s require the design of a more complex sedimentation tank. Mathillo Semrang has a maximum stream source flow-rate of 0.32 L/s and employs the use of a Type 2 tank.

Boycott Effect and Inclined Plate Settling

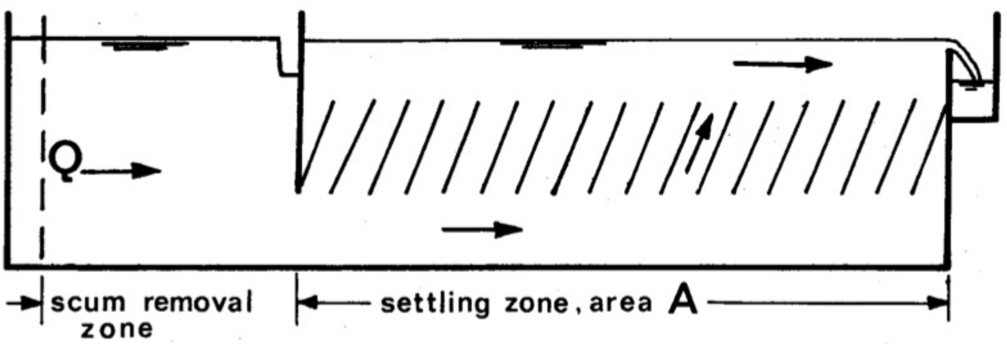
The Boycott Effect describes the increase in particle settling rate due to the presence of an inclined surface. This phenomenon was first described by Boycott in 1920 with the discovery that if "defribinated blood is put to stand in narrow tubes, the corpuscles sediment a good deal faster if the tube is inclined than when it is vertical" (Boycott, 1920).

The increase in settling rate can be described by imagining a settling particle within an infinite quiescent medium in a container with vertical walls. The particle must travel through the medium until it reaches the bottom surface of the container. But if the particle is inside a vessel containing an inclined surface, the particle has the opportunity to make contact with a surface and slide down to the bottom of the container without having to traverse the total height of the container. The increase in particle settling rate can therefore be seen as a decrease in settling distance (Demir, 1995) and an increase in the surface area available for settling (Davis & Acrivos, 1985).

Inclined Plate Settlers – Description and Design

Inclined plate settlers (Figure 4) are high rate sedimentation devices that consist of a series of inclined parallel plates forming channels (plate stack) into which a particle containing solution can be fed for separation. The plate stack is normally installed between a parallel inlet and outlet channel (Leung & Probstein, 1983).

Figure 4: Cross-section of an inclined plate settler



Water enters through the inlet and is forced to flow up through the channels created by the plate stack to the outlet area where the effluent is collected in the outlet chamber (Foellmi & Bryant, n.d.; Leung W-F & Probstein, 1983). As the water flows through the plate stack channels, the particles settle onto the downward facing walls of the inclined plates and slide down to the bottom of the settler where they are collected (Davis, Zhang, & Agarwala, 1989).

IPS designs have the capacity to settle out very fine suspended particles at a high rate. The settler capacity per unit volume can be made large without substantial increase in the footprint of the tank (Foellmi & Bryant, n.d.). The ratio of floor area needed for conventional sedimentation basins to the floor area for IPS designs can range from 8:1 to 10:1.

Influence of Plate Dimensions on IPS Design

A relationship developed by Huisman (Huisman, 1986) shows the relationship between specific plate parameters and the increase in effective settling rate.

Figure 5: Schematic of settling particle between two inclined plates.

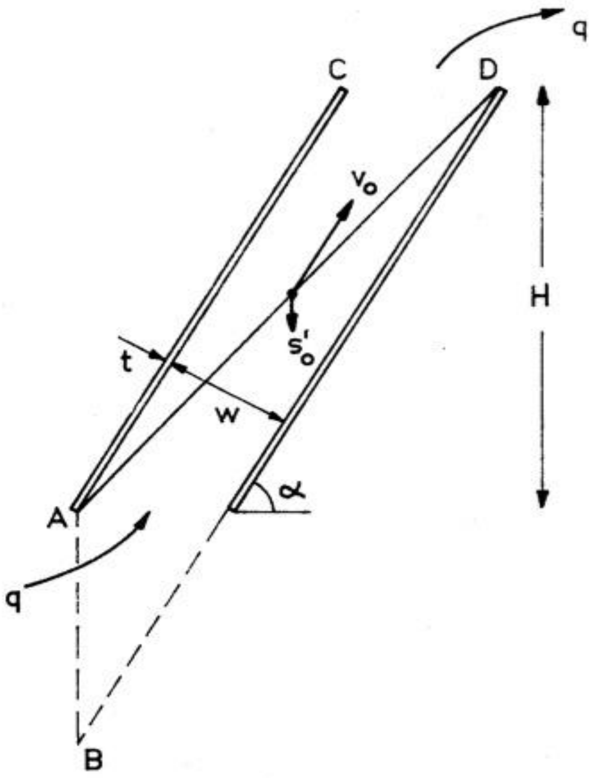


Figure 5 shows the critical dimensions considered in the design of IPS tanks, where plates of thickness *t*, angle of inclination to the horizontal α, inter-plate distance *w* and tank height *H*, the efficiency or removal ratio of the settling tank is given by Equation 2 (Huisman, 1986):

$$\frac{S'_o}{V} = \frac{w \ \sin \propto}{H \ \cos \propto \ + w} \quad (2)$$

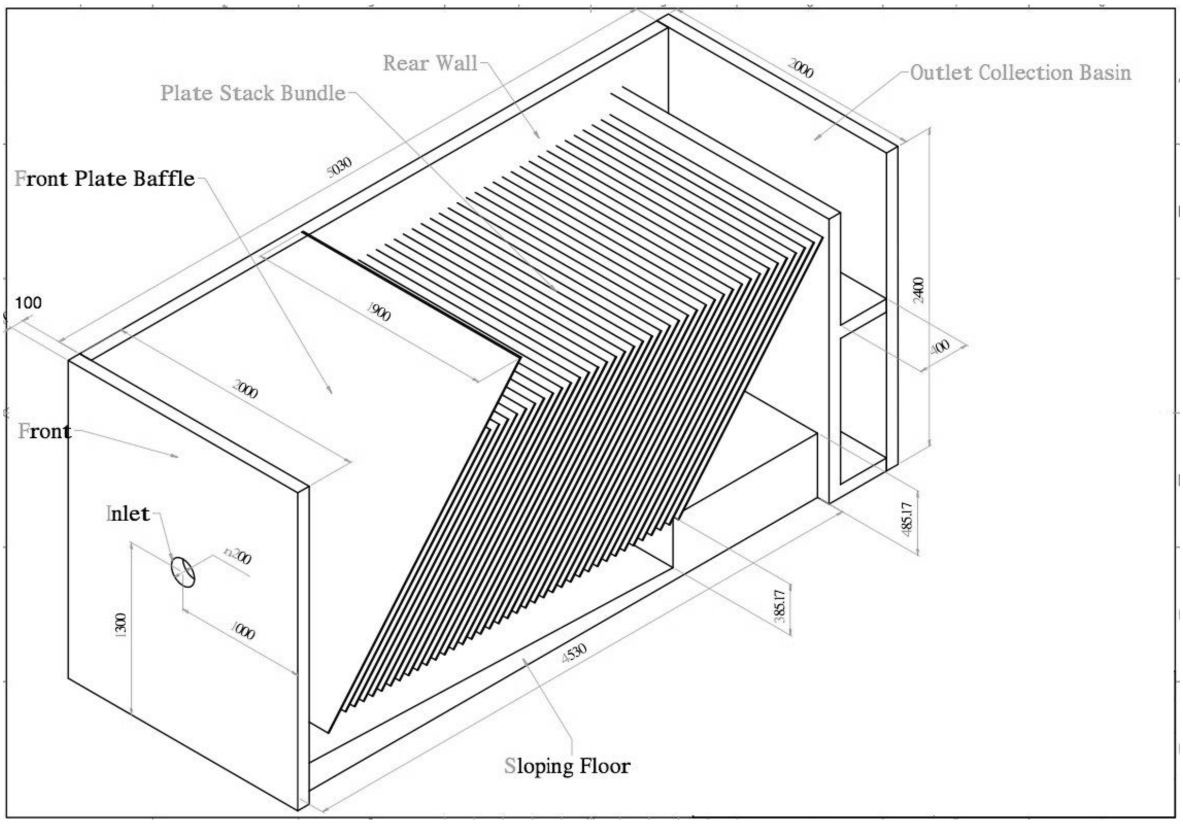
The improved setting rate (Equation 3) is described as a function of the settling rate without the plates and the plate dimensions:

$$S_o = S'_o \ \frac{H \ \cos \propto}{w + t} \quad (3)$$

Full Scale Model Design

The general dimensions of the full-scale design are shown in Figure 6. Detailed design drawings are given in Figures 11 and 12 contained in appendices 2 and 3.

Figure 6: Cross section of full-scale IPS design

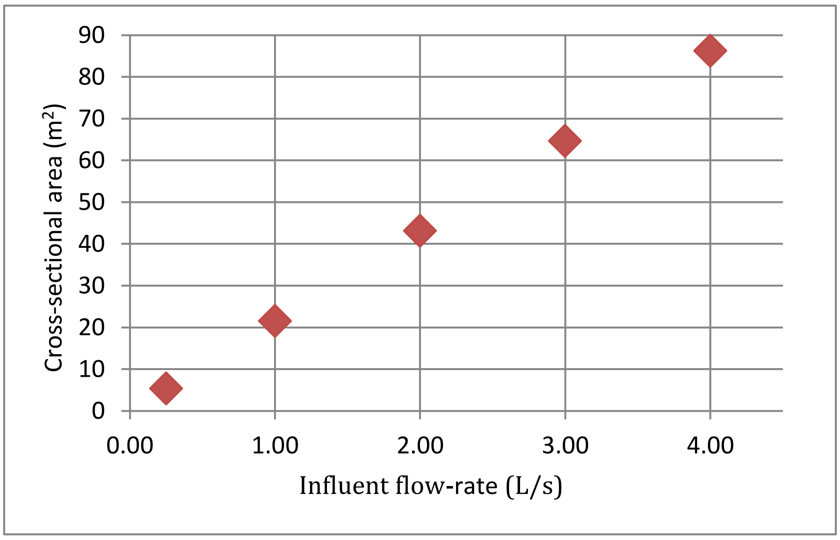


Stokes' Analysis

Mathillo Semrang spring and stream sources can be considered dilute suspensions with laminar flow; therefore, Stokes' analysis was used to determine the theoretical cross-sectional area needed for adequate settling.

A minimum particle size of 10 microns was used as the basis for design as it is the smallest expected size of the soil based granitic particles typical of the region. The cross-section areas required for the settling of the particle with respect to various influent flow-rates were calculated and are shown in Figure 7.

Figure 7: Stokes' analysis for cross-sectional area of tank required for various influent flows



A cross-sectional area of 86.26 m^2 is necessary to ensure adequate settling of 10 micron particles with an influent flow-rate of 4 L/s; this equates to a diameter of 10.48 m.

Huisman's Analysis

A summary of the design parameters chosen for the full-scale IPS plate scale design is listed in Table 1:

Table 1: Parameters chosen for the full-scale IPS design using the Huisman analysis

Parameter	**Value**
Plate stack height (H)	1.5 m
Plate length (L)	1.96 m
Plate width (W)	1.9 m
Plate thickness (t)	0.01 m
Plate spacing (w)	0.05 m
Angle of inclination (α)	50^o
Cross-sectional area of plate stack (A)	5.10 m^2

The height of the plate bundle was the crucial element for design and it was necessary for this height to be less than 2 m in to allow a tank height of no greater than 2.5 m to be safely constructed manually. A plate thickness of 0.01 m was chosen to allow structural integrity when manually inserted and removed into grooves constructed in the tank wall. A plate spacing (*w*) of 0.05 m was chosen for a similar reason. The plate inclination angle of 50^{o} was chosen as it allowed for a small cross-sectional area (5.1 m^2) and effective plate cleaning (Culp, Hansen, & Richardson, 1968; Shamim & Wais, 1980).

Inlet Design

If the plate bundle is situated in a rectangular tank, there is the loss of a significant amount of area that would otherwise be utilised. Industry mitigates this loss in area by using stabilising structures to construction the clarifier as a tilted piece of equipment without any vertical walls. Although viable, this solution is impractical where ease of construction is necessary. The inlet area was designed to make use of the wasted space associated with the inclination of the plate bundle with adequate positioning of the inlet opening and the lengthening of the first plate in the bundle to create a suitable baffle for momentum dispersion and to reduce short-circuiting.

Outlet Design

The outlet design consists of an overflow weir leading to an effluent collection basin containing a submerged outlet. This prevents the carry over of scum into distribution. Due to the length of the tank and the low flow-rate of the influent entering the system, it can be assumed significant settling will occur before the outlet is reached and therefore the use of an overflow with submerged outlet is appropriate.

Sludge Collection Design

The floor of the tank has been constructed with a slope of 2 degrees to allow the collection of sludge to be removed during the washout cycle.

Building Materials and Construction Considerations

The current round sedimentation tanks are simple to construct with minimal cost necessary. The tanks exist almost entirely as Ferrocement structures with a stone foundation. The piping, valves and manholes are constructed from more valuable materials.

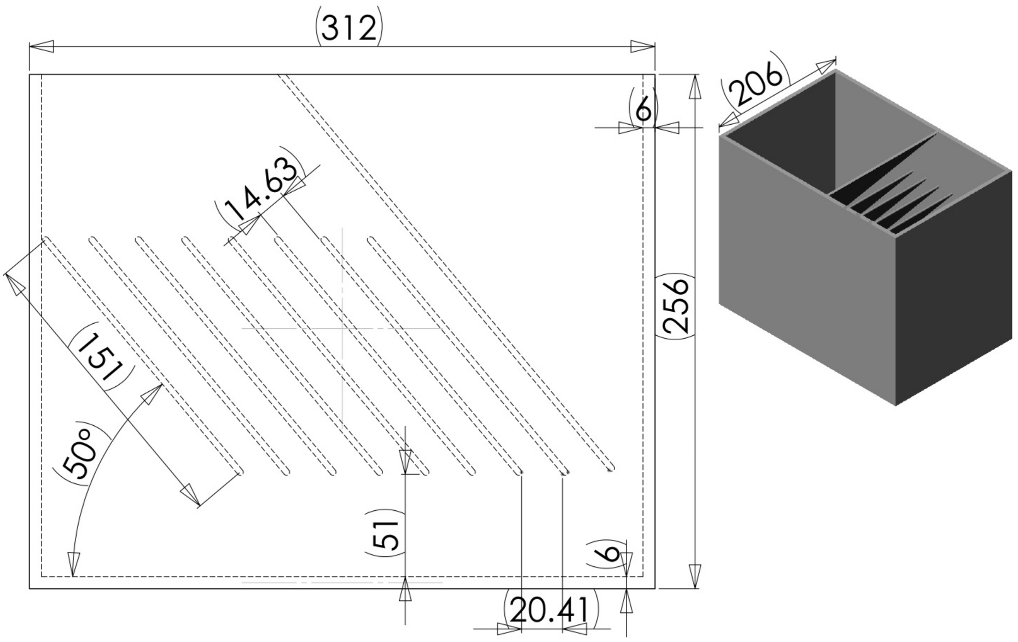
To ensure the full-scale design also remains cost effective, it was decided the construction of the tank would be similar to that of the round sedimentation design. The tank will sit on a foundation of stone and may be dug into the ground if necessary. The outer walls and floors will be Ferrocement with the use of adequate steel reinforcement where appropriate. A corrugated iron roof will protect the system from the weather. The inlet and outlet piping and valves will remain the same specification as is available currently to the Mathillo Semrang community.

The plates would ideally be constructed from sheet metal such as stainless steel, plastic (polyethylene, ABS or similar) or even a marine ply (Schultz & Okun, 1984) but these materials are currently unavailable in rural communities. An alternative suggestion would be the use of inclined plastic tubing or an ABS hexagonal matrix instead of a plate design. This would require the redesign of the system and may prove challenging in construction and maintenance, however such systems are common industrially. There is need for further research and liaison with the local community members and NEWAH as to the most appropriate material to be used for the IPS design.

Laboratory Testing

A Perspex model (Figure 8) was built to test the integrity of the full-scale design. A perfect scale model was difficult to achieve, as the scaling of the plate thickness resulted in non-realistic dimensions.

Figure 8: Laboratory IPS model



The model does not include an overflow weir or a separate effluent collection chamber with a submerged outlet. The outlet is placed very close to the edge of the plate bundle and the influent opening is placed perpendicular to the outlet opening. There is no sloping floor leading to any washout system.

An overflow rate of 2.21×10^{-4} m/s with a maximum flow-rate of 421 mL/min was calculated using Huisman analysis for the scaled design in Figure 8.

A simple laboratory experiment was conducted to test the ability of the scaled model to clarify solutions containing calcium carbonate particles ranging from 15 to 40 microns in size. The influent solution was pre-prepared by settling a small amount of Omycarb 40 (calcium carbonate) in a beaker to collect the 15 micron particles needed for experimentation. The sediment was diluted with an appropriate volume of water to provide a solution with a turbidity of 20-25 NTU.

A peristaltic pump allowed the calibration of the influent to an initial 55 mL/min, or approximately 13 % of the maximum flow-rate. The model tank was filled with water and a particle solution added. When the inlet chamber solution was recorded as having a turbidity of approximately 25 NTU, the effluent turbidity was measured approximately every 10 minutes to gauge operation of the device. When the effluent turbidity reached the same value as the influent, the process was stopped and the tank was emptied and cleaned.

The procedure was repeated at flow rates of 150 and 253 mL/min (36 and 60 % of the maximum flow-rate respectively) and at 421 mL/min (maximum flow-rate).

Results

Figure 9: Effluent turbidity of varying influent flow-rates entering the laboratory device.

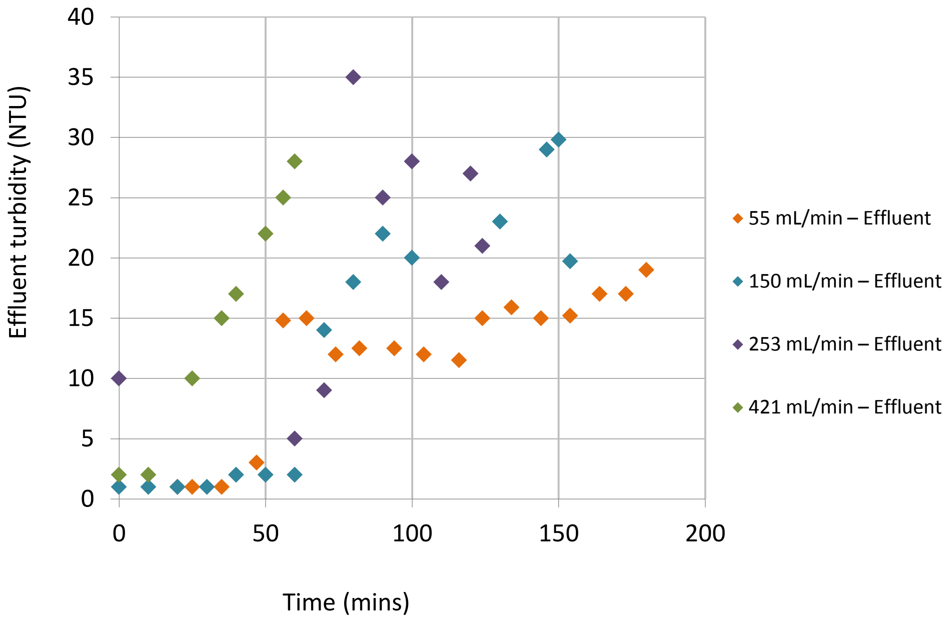


Figure 9 indicates that an increase in flow-rate from 13 to 60 % of the maximum flow-rate (421 mL/min) resulted in a direct increase in effluent turbidity of 40 %. With the exception of the maximum flow-rate, the system produces reasonable effluent less than 5 NTU within the first 60 minutes of operation. After this period, a dense build up of particles was observed in the sludge collection area. This build up of particles resulted in short-circuiting of the system either through the first or last channel for the low and higher flow-rates respectively. This result was noted by an increase in effluent quality after the 60-minute period. This time frame may signal the point at which a washout period is necessary or more likely, that a continuous bleed of this material is required. Calculation indicates that at full scale this washout period must occur every two hours. This timeframe is unfeasible and suggests that washout may need to occur continuously at a low flow-rate to ensure adequate clarification.

If the results are indicative of the performance at full-scale operation, it can be seen that the most promising operational flow-rate of the system would be only 10% of the maximum design flow-rate or 0.40 L/s. This is suitable for Mathillo Semrang as the reported stream source flows are on average only 0.32 L/s but the design would not be robust enough to handle large flow and particle loadings, without continuous washout or a better design of the influent area or washout area to prevent short circuiting.

Most pertinently, the experimental results revealed the inherent importance of the design of the inlet chamber and sloping floor. An increase in area of the inlet chamber as well as the construction of a steep sludge collection basin leading to a sump would allow an increase in momentum dissipation and an increase in system performance. These changes although crucial, are a challenge for the design as the increase in dimension of the inlet and sludge collection areas results in an increase in footprint and vertical height of the system, proving difficult for safe construction.

As the laboratory model was not perfectly representative of the system the above conclusions require validation. Experimental testing with a wider range of feed flow-rates, particle concentrations and turbidities would be necessary to fully understand the system performance.

Conclusions and Recommendations

A high rate sedimentation device, the inclined plate settler (IPS) was designed to combat the turbidity issues arising from stream sources in the rural hilly community of Mathillo Semrang, Nepal.

The footprint of the design is 10.5 m^2 with the theoretical capacity to treat a maximum influent flow-rate of approximately 4 L/s. This is a reduction in footprint of up to 76% from the current round sedimentation design (42 m^2). The design allows for the construction of a single device to replace the five separate devices currently used. The design is gravity driven and requires no electricity to operate. Its construction is similar to that of the current design and is therefore assumed to be economically viable.

Laboratory experimentation revealed the most optimum operating flow-rate is 10 % of the design flow-rate. This conclusion needs further investigation and further experimentation is necessary to determine the system robustness to a range of particle size and loadings. Particle size distributions of the effluent and flow modelling of the system may be useful in revealing the shortcomings of the design.

Collaboration with NEWAH and the Mathillo Semrang community is necessary to supplement the design.

Acknowledgements

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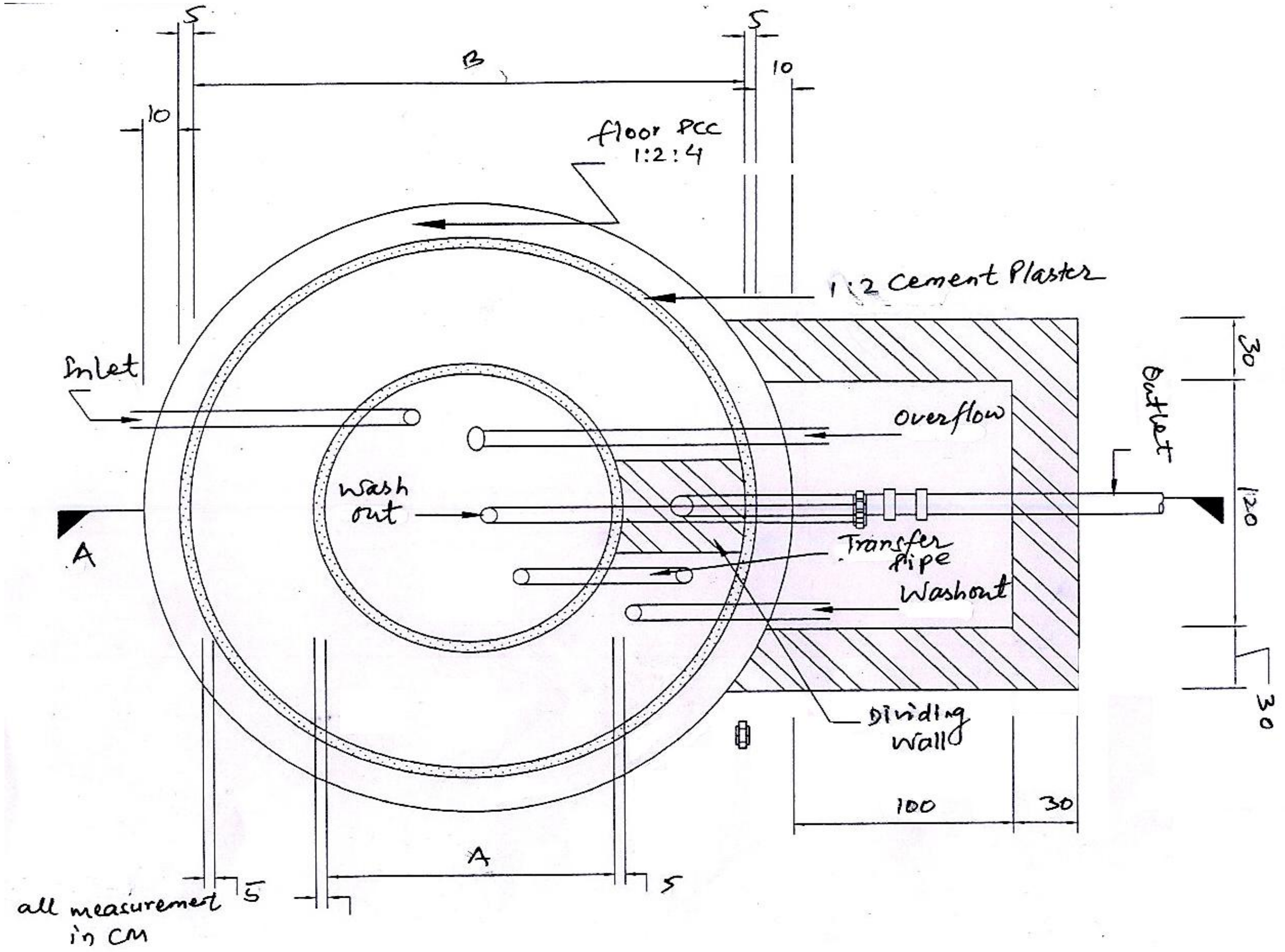
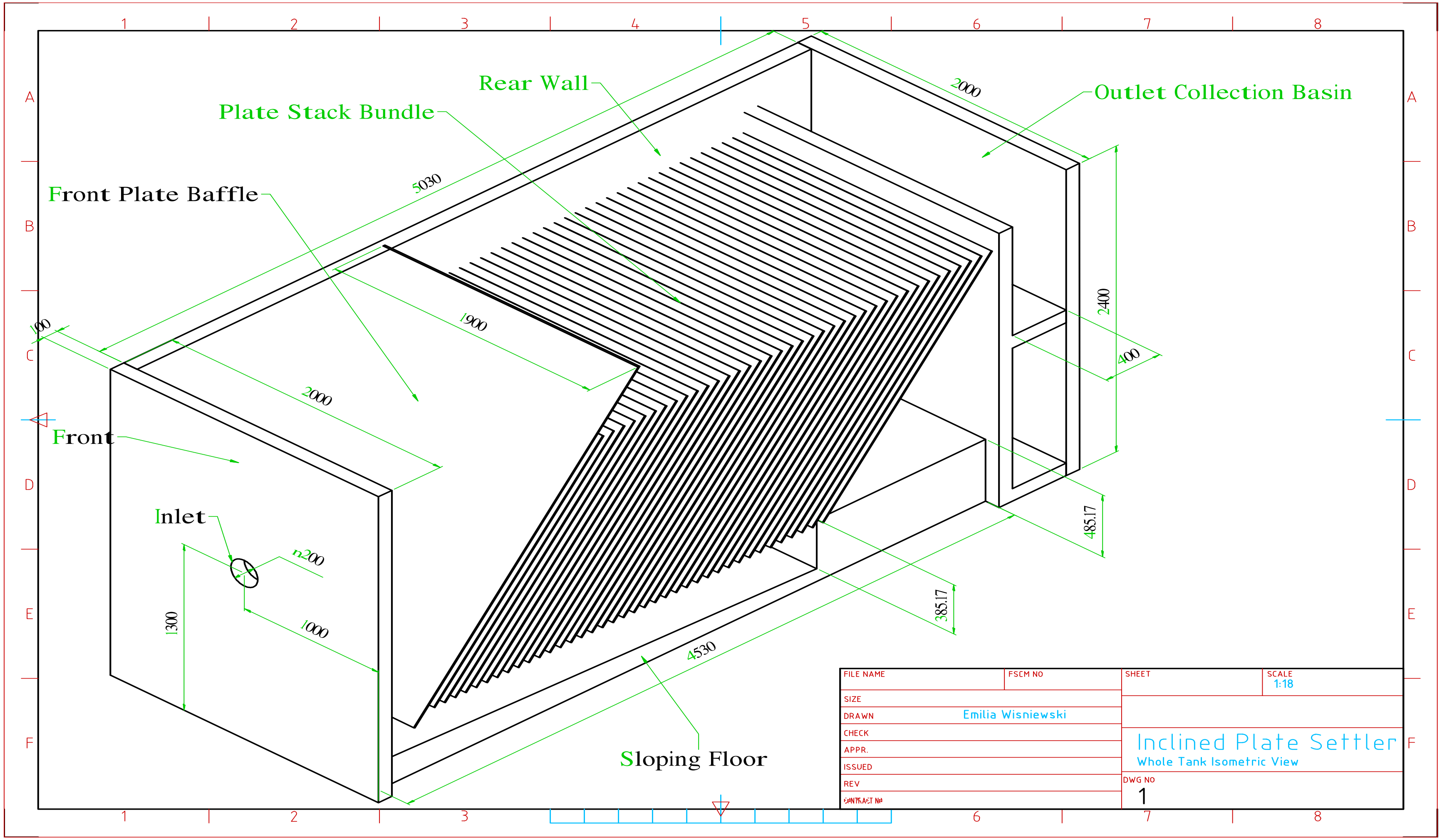
Appendix 1

Figure 10: Top view of Ferrocement water filter tank (Nepal Water for Health (NEWAH), 2012)



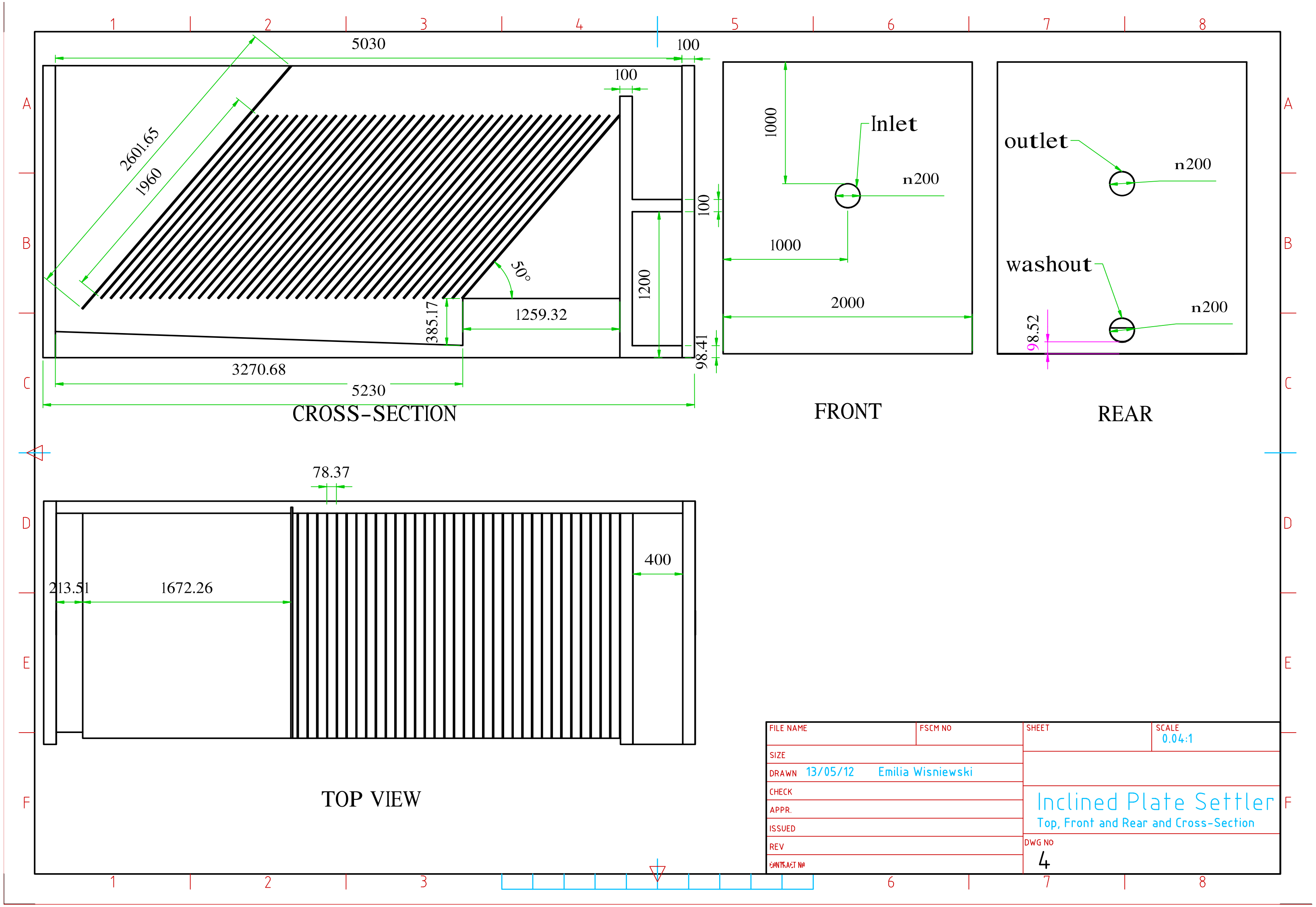
Appendix 2

Figure 11: Isometric view of inclined plate settler design showing whole tank



Appendix 3

Figure 12: Top, front, rear and cross-sectional views of the inclined plate settler design



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