Final Report

Solar Farm Design Optimisation, Sustainability Options & Rainfall Runoff Experiment

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Executive Summary

The following documents and collates information concerned with the 'Solar Farm Design Optimisation & Sustainability Options' carried out by the Jacaranda Flame Consulting (JFC) junior consulting team (Group 12) with clients Robert Bird Group (RBG). The document is concerned with three aspects or deliverables within the bounds of the project being the 'Rainfall Runoff Experiment', 'Pavement Design Optimisation' and 'Stormwater Scouring Protection Optimisation'.

Within the rainfall runoff experiment, findings denote that an elevation or tilt angle of 25 degrees of the solar panel depicts an influx in both total water runoff as well as peak discharge rate in comparison with 35, 45 tilt angles and the no panel case. Furthermore, multiple new variables and factors have been found through investigations that need particular attention and it is recommended that future tests be conducted with the proposed changes to setup and investigation circumstances or measures. Some of these variables include:

- Weather & Wind Conditions
- Rainfall Coverage
- Panel Placement
- Type of Synthetic Grass
- Synthetic Grass Saturation

Within the pavement optimisation review and investigation of this project, geosynthetics have been the primary focus of approaches and materials to be utilised within solutions. Product market research and comparisons has denoted that the following are viable options to replace pavements within solar farms:

- Geotextiles
  - Bidim Green Non-Woven
  - TenCate - Mirafi RSi
- Geogrids
  - DuraGridX
  - masraGrid - Poly Geogrid 40

Similarly, within the scouring optimisation review and investigation of this project, the approaches to be proposed via market research and comparisons include:

- Reinforced Turf Mat
- Geocell
- Geotextile Sand Container

Contents

List of Acronyms

AEP Annual Exceedance Probability.

CBR California Bearing Ratio.

CCS Cellular Confinement System.

FEA Finite Element Analysis.

GCLs Geosynthetic Clay Liners.

GDB Geocomposite Drainage Blanket.

GMA Geosynthetic Materials Association.

GST Goods and Services Tax.

HDPE High-density Polyethylene.

JFC Jacaranda Flame Consulting.

NRCS Natural Resources Conservation Service.

NSW New South Wales.

PA polyamide.

PET Polyethylene terephthalate.

PP polypropylene.

PVC Polyvinyl Chloride.

RBG Robert Bird Group.

UOM Unit of Measure.

UV Ultraviolet Radiation.

WWTP Wastewater Treatment Plant.

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1 Introduction

1.1 Project Description

In 2018, Robert Bird Group (RBG) led the development project of both the Wemen and Swan Hill Solar Farms. These solar farms embody the values of the organisation concerned with environmental sustainability and therefore, the organisation has proposed an optimization project in 2022. The primary aspects of improvement that can maximise the organisations sustainability and cost goals in relation to solar farm design include;

- Research into product types that can pose benefits in optimising design of pavements accommodating light traffic throughout solar farms.
- Research into products that can optimise the design of stormwater drainage scouring protection measures within the stormwater system of the solar farms.
- Optimising material utilisation when undertaking and/or developing the investigations and implementation methodologies of the previous two dot points.

For each of these aspects, a primary emphasis has been denoted upon the design solutions to prioritise sustainability and cost effectiveness.

Furthermore, RBG has voiced an avenue of investigation and research into the effect of water flow within the confines of a solar array. This aspect of research is to be carried out in the form of a physical experiment determining the effects of solar panels upon water runoff.

The current pavement employed within the grounds of typical solar farms are evaluated as slightly conservative and improvements to both costs and sustainable practices can be maximised by researching alternative approaches to current standard paving designs and methods. This would involve investigating replacement materials such as geosynthetic products and comparing benefits amongst multiple differing design solutions.

Similarly, the current stormwater system employs standardised rock protection in areas of scouring and forceful water flow. Therefore, research of alternative products and methods can optimise scouring protection measures and designs. This can assist to combat both flood risks and scouring. Therefore, this project can ultimately allow the solar farm designs to be more environmentally sustainable, environmentally tolerable and pose a lower impact upon the natural landscapes.

As consultants, our team's collective role is to research, investigate and propose optimisations and design(s) approaches that address each of the THREE goals of the project (mentioned above) within a six-week period. Therefore, a review of the pre-existing or conventional design measures must be carried out, dictating our research opportunities and implementation strategies. Furthermore, direct comparisons and an evaluation of both alternative approaches and pre-existing measures are to be carried out to determine the most effective and desirable solution capable of satisfying the aforementioned project goals.

2 Literature Review of Rainfall Runoff Experiment

2.1 Background

The motivation of the rainfall runoff experiment is to find out if there is a discernible effect of panels impacting natural rates of water discharge.

The number of solar farms in the application of Solar panels has increased sharply as an effective and efficient way to generate electricity in recent years. However, their hydrological impacts have not been studied. The goal of this study was to determine the hydrological effects of solar farms and examine whether or not measures are needed to control runoff volumes and rates.

As the presence and impacts of climate change become more of a prevalent issue to members of society, many individuals, organisations, as well as businesses are beginning to make changes to reduce their carbon footprints, favouring clean and renewable energy instead of fossil fuels. Clean, renewable energy is on the rise, and with that comes investments in the development of alternative energy sources such as wind and solar farms.

2.2 Australian Real Rainfall Intensities

Rainfall intensities within this investigation are required to replicate as closely the realistic behaviour of rainfall and flow within solar arrays and complementing environments. The current rainfall intensities that are aimed to be replicated are sourced from the, 'Civil and Structural Engineering Design Report' supplied by the Robert Bird Group. See table below for the breakdown of rainfall intensities for West Wyalong that are being referred to during this investigation. These values are the Annual Exceedance Probability (AEP) in mm/min over the given duration of time defined within the chart.

	Annual Exceedance Probability (AEP)						
Duration	**63.2%**	**50%#**	**20%***	**10%**	**5%**	**2%**	**1%**
1 min	1.55	1.77	2.49	2.99	3.50	4.21	4.77
2 min	2.64	3.02	4.27	5.14	6.01	7.10	7.93
3 min	3.62	4.15	5.84	7.03	8.21	9.74	10.9
4 min	4.48	5.13	7.21	8.67	10.1	12.1	13.6
5 min	5.24	5.99	8.41	10.1	11.8	14.1	15.9
10 min	7.99	9.11	12.8	15.3	18.0	21.6	24.6
15 min	9.79	11.2	15.6	18.8	22.0	26.6	30.2
20 min	11.1	12.7	17.8	21.4	25.1	30.2	34.3
25 min	12.2	13.9	19.5	23.5	27.5	33.1	37.6
30 min	13.0	14.9	20.9	25.2	29.5	35.5	40.3
45 min	15.1	17.2	24.2	29.1	34.1	40.9	46.3
1 hour	16.6	18.9	26.6	32.1	37.6	44.9	50.8
1.5 hour	18.8	21.6	30.4	36.5	42.7	51.0	57.5
2 hour	20.6	23.6	33.3	40.0	46.7	55.7	62.7
3 hour	23.5	26.9	37.8	45.4	52.9	63.1	71.0
4.5 hour	26.7	30.6	42.9	51.5	60.0	71.6	80.7
6 hour	29.3	33.6	47.0	56.4	65.7	78.5	88.6
9 hour	33.5	38.2	53.4	64.0	74.6	89.5	101
12 hour	36.7	41.8	58.4	70.0	81.7	98.1	111
18 hour	41.4	47.2	65.7	79.0	92.4	111	127
24 hour	44.9	51.0	71.1	85.6	100	121	138
30 hour	47.6	54.0	75.3	90.7	107	129	147
36 hour	49.7	56.4	78.6	94.9	112	135	154
48 hour	52.9	60.0	83.6	101	119	144	164
72 hour	57.0	64.5	90.1	109	129	155	176
96 hour	59.5	67.5	94.2	114	135	161	182
120 hour	61.4	69.7	97.2	117	138	165	186
144 hour	62.9	71.5	99.6	120	140	167	188
168 hour	64.3	73.2	102	121	141	168	189

Figure 2.1: AEP Values in mm/min

In fulfilling the investigation outlined upon the project scope, the decision has been made to utilise the following rainfall intensities as references:

Table 2.1: Rainfall Intensities

Annual Exceedance Probability (AEP) (%)	**Intensity (mm/min)**	**Rainfall Event Classification**
63.2	1.048	1 in 1 Year Event
10	2.02	1 in 10 Year Event
1	3.18	1 in 100 Year Event

In reality however, the rainfall intensities utilised for the investigation is aimed to be an intensity within 1 in 1 year to 1 in 2 year rainfall event. Therefore, we are striving for readings of rainfall intensity within the range in the realm of 1.048-1.198mm/min.

This is done to accommodate and focus the experiment on a majority common situation or circumstance. Furthermore, due to the available setup, equipment and materials of the experiment we have also limited the extremity of the weather event we are aiming to model.

2.3 Simulated or Computer Generated Models

2.3.1 Case Study: Hydrologic Response of Solar Farms

Aim

The objective of simulating the rainfall runoff for both the pre-developed and post-developed solar farms is to investigate the hydrologic responses in terms of runoff volumes and flow rates, as well as the need for additional storm water management on site.

Background

- Solar panels are impermeable and are usually placed over permeable land.
- Solar panels are usually designed to allow rotation to achieve optimal efficiency in response to variations in the angle of the sun (from 22° in summer to 74° in winter, depending on the latitude).
- Erosion issues due to water draining may occur in solar farms.
- Required to have space for maintenance vehicles.
- Infiltration losses would be expected depending on the land cover type.

Model Development

A computational model was development in order to investigate the impact of solar panels on runoff characteristics as shown in the Figure below [1]. A simulated segment of solar farms can be divided into three sections, which are wet, dry and spacer respectively.

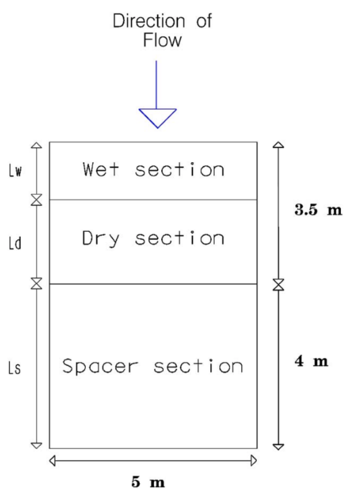


Figure 2.2: Computational Model [1]

Where,
Wet Sections: The area that the rain directly falls on to the ground, corresponding to the variation of solar panels' placed angles.
Dry Sections: The area underneath the solar panel that is not exposed to precipitation.
Spacer Sections: The area designed for the utilisation of maintenance vehicles.

Assumptions

- Assume the ground condition was fully saturated, thus the infiltration loss rate was assumed to be constant during a storm event.
- The outflow rate was assumed to be the flow from the most down-gradient section.
- Rainfall intensity is consistent over the area.
- Rainfall data was obtained from Natural Resources Conservation Service (NRCS) Type II Storm [2].

Independent Variables

- Solar Array Layout & Spacing

Dependent Variables

- Pre-panelled and panelled conditions
- Amount of precipitation: 25-year storm and 2-year storm
- Ground Slope: The ground slope was changed from 1% to 5% with all other parameters remaining the same.
- Soil Type: Soil type was changed by changing the loss rate in the simulated model.
- Panel Angle: The lengths of the wet and dry sections changed depending on the angle of the solar panel. Besides, surface flow velocity is proportional to the slope. To investigation the effect of panel angles, angles of 30°and 70°were selected to simulate the summer and winter average placement angles respectively.
- Storm Duration: To evaluate the impact of storm duration, analyses were conducted for 6-h storms, testing magnitudes for 2-, 25-, and 100-year return periods, and comparing the results to those for 2-h rainfall events.
- Ground Cover: Depending on the local sunlight duration, solar panel coverage areas and traffic volume, ground conditions of spacer area could be bare ground, patches of grass or grass. In the computational modelling, the variations of ground coverage were achieved by changing the magnitudes of surface roughness in Manning's equation.

Discussion

The investigation on the hydrological impact revealed the following observations:

- Amount of precipitation: By comparing the effects of 25-year storm and 2-year storm, it was found that different rainfall intensities would have minimal impacts on the hydrologic response of solar farms as the peak runoff and the time to peak did not have significant differences.

- Ground slope: With the slope increased, the discharge difference between the pre- and post-development solar farms was less than 1%, which indicated that the performance of solar farms was less affected by the ground slope.

- Soil types: For the soil condition with high loss rate, the actual runoff volumes and flow rates were increased. However, not the relative effect of post-development solar farms in comparison with unpanelled conditions.

- Panel Angle: The runoff characteristics for 30°and 70°were compared to the base condition angle of 45°. The result showed that when other site conditions remained constant, 30°case was associated with an increase in runoff volume, while the angle of 70°was associated with a decrease. However, the differences were less than 0.5%, which could be negligible. Thus, the angle of solar panel had minor impact on discharges.

- Storm duration: The hydrologic response of solar farms was not affected by storm duration. Specifically, for both panelled and pre-panelled circumstances, runoff volumes for the 6-h storm were 34 percent greater than those for the 2-h storm. In contrast, when comparing the pre-panelled condition to the panelled condition, the increase in runoff volume during the 6-h storm was less than 1% regardless of the return period. Meanwhile, peak discharge and time-to-peak were not significantly different between panelled and pre-panelled conditions.

- Ground cover: The hydrographs for 12-s time and 3-s increments were shown in Figure 2.3 and 2.4. For 12-s time intervals, the runoff within every segment was discharged at the end of each time increment continuously, resulting in no flow attenuation. The results revealed a 7% increase in storm runoff from the grass-covered scenario to the gravel-covered scenario. The gravel ground cover increased peak discharge by 73% compared to the grass ground cover without the panels. Time-to-peak was 10 minutes less with gravel than with grass, reflecting the effect of surface roughness differences as well as runoff velocities.

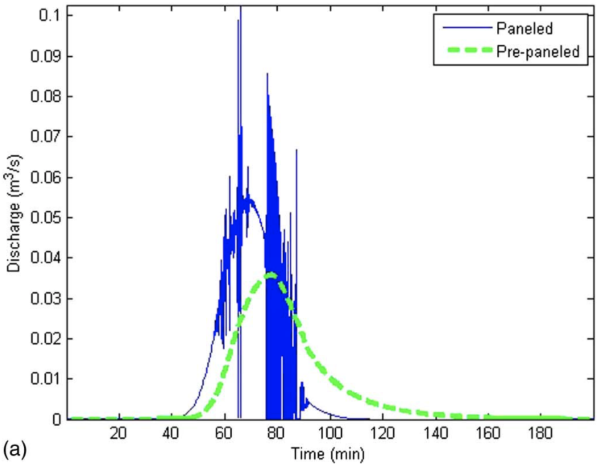


Figure 2.3: Hydrograph with Time Increment of 12s [1]

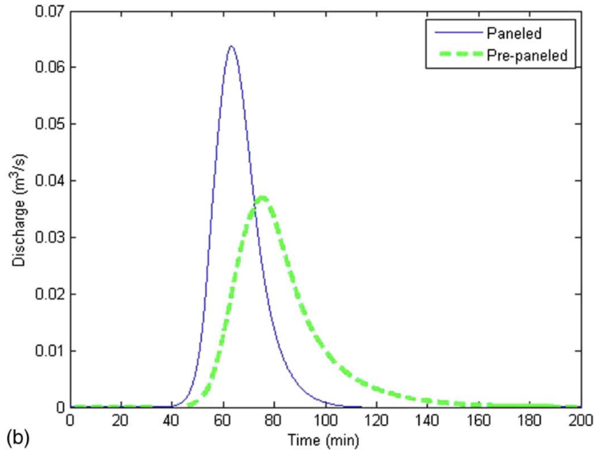


Figure 2.4: Hydrograph with Time Increment of 3s [1]

Conclusion

To investigate the hydrologic response in terms of runoff volumes and discharges, a unit section of pre-installation solar farms was modelled and then with solar panels added. Various sensitivity analyses were conducted regarding the amount and duration of precipitation, ground slope, soil type, angles of solar panel placement and ground cover conditions. Except for ground cover conditions, the results showed that installation of solar panels had minor effect on hydrologic responses regarding runoff discharges, peak volumes and time-to-peak. However, the hydrologic responses changed significantly with the variation of land-cover types. It was found that there was a significant increase in runoff volume and peak discharge if the panels were placed over gravel or pavement rather than patchy grass or bare ground, which was approximately 100%.

Suggestions

A well-maintained ground cover to be placed under the solar panels or in the spacer section is strongly recommended. If bare ground is considered unavoidable or is foreseen to be a potential issue in the future, a buffer section is suggested to be implemented to control the runoff volume and infiltration losses in solar farms [3].

2.4 Typical Solar Panels Orientation and Tilting Angels

Solar panels installation differs based on their geographic locations throughout the world. The main reason behind this is that the location of the sun varies and panels are required to be directed to the positioning of the sun to maximise energy generation over a specific period. Ideally, it is when the sun is hitting the panels at a 90° angle [4]. Two main factors that influence such an angle are the orientation such as North, East, West and South, and the angles of the panels from the surface of the Earth. As Australia being in the southern hemisphere, sun is predominantly coming from the North. Although there might be some differing throughout the seasons, ideally, solar panels should be placed facing as close to true North as possible to reduce impacts that the Winter season has on efficiency [4].

Th angle that the panels are facing up into the sky is the crucial factor in tilting. Generally, the ideal angel for solar arrays should be the same as the site's geographical latitude. For example, the ideal solar panels angel in Sydney is at 33.9°, as this is equal to latitude angle of the NSW capital [5]. The optimum angle for solar panels range between 20° to 40° for around 90% efficiency, where 32° angle is the best. However, if the panels are placed below 5° angel or larger than a 60° angle, the energy efficiency will become an issue [4, 5]. Therefore, the optimum solar panels angles chosen for the experiment will be at 25°, 35° and 45° angels to reflect a real life situation of solar arrays.

2.5 Relevant Formulae

2.5.1 Rainfall Intensity

$$mw(63.2) = \rho \times AG \times \frac{(63.2)AEP(5)}{5}$$

$$mw(10) = \rho \times AG \times \frac{(10)AEP(5)}{5}$$

$$mw(1) = \rho \times AG \times \frac{(1)AEP(5)}{5}$$

Figure 2.5: Rainfall Intensity Formulations

where;

- mw = the mass(kg) of of water in the container after 1 minute
- AG = the area(m^2) of the artificial grass receiving water from the hose head

- $\rho = 997$kg the density of water
- (63.2) AEP (5) is the amount of rainfall (m) that has an annual exceedance probability in 5 minutes of 63.2%
- (10) AEP (5) is the amount of rainfall (m) that has an annual exceedance probability in 5 minutes of 10%
- (1) AEP (5) is the amount of rainfall (m) that has an annual exceedance probability in 5 minutes of 1%

According to the Bureau Meteorology Australia, (63.2) AEP (5) = 0.0159m, (10) AEP (5) = 0.0101m, (1) AEP (5) = 0.00524m [6].

This formula ended up being replaced by a simple measuring container on the apparatus. The amount of water collected in the container in 1 minute is the intensity for the whole setup.

2.5.2 Discharge/Unit Conversion

the discharge in g was converted to cm^3 with 1g = $1cm^3$, the discharge per second was calculated by dividing the discharge in cm^3 in a period of time by the time in second.

2.6 Synthetic Grass

The surface roughness affects the water flow velocity and could affect the runoff result because of the grass retarding effect. Ideally, the synthetic grass used in the experiment should have the similar roughness coefficient (Manning's coefficients) as the real grass in solar farms. There are manning coefficients of the grass provided from the client's previous project. However, to determine the Manning's coefficient of the synthetic grass takes extra time and effort. For simplicity, the synthetic grass is selected based on the client's suggestion.

3 Methodology

3.1 Aims

- To find out if a solar panel on grass would increase surface runoff during a rainfall event compared to no solar panel on grass.
- To find out if the angle of a solar panel would increase surface runoff on grass.

3.2 Assumptions

The assumptions involved or established within this experimental investigation includes the following:

- No water seeps out of the tape.
- Evaporation is negligible.
- The rainfall intensity is consistent over the area.
- The apparatus will be dried adequately between tests.
- Effect from wind is negligible.

3.3 Control Variables

The control variables established within this experimental investigation includes the following:

- Hose Head Selection
- Intensity of Rainfall
- Area of Synthetic Grass
- Area of Plastic Cellular Sheet
- Number of Plastic Cellular Sheet
- Position of Hoseheads
- Time of each Test
- Time Intervals between Data Recording
- Slope of Ground/Base Table
- Height of Plastic Cellular Sheeting over Synthetic Grass

3.4 Equipment List

The following section gives a list of all equipment involved within the experiment. Further details such as, material cost, dimensions and sources can be found in Appendix B.

- Table
- Weight Scale (5kg)
- Stand
- Bucket or Container (3L)
- Guttering (2.4m)
- Synthetic Grass (1x3m)
- Plastic Cellular Sheeting (1x0.6m)
- Cone Hose Head/Nozzle
- Protractor
- Level

3.5 Equipment Setup

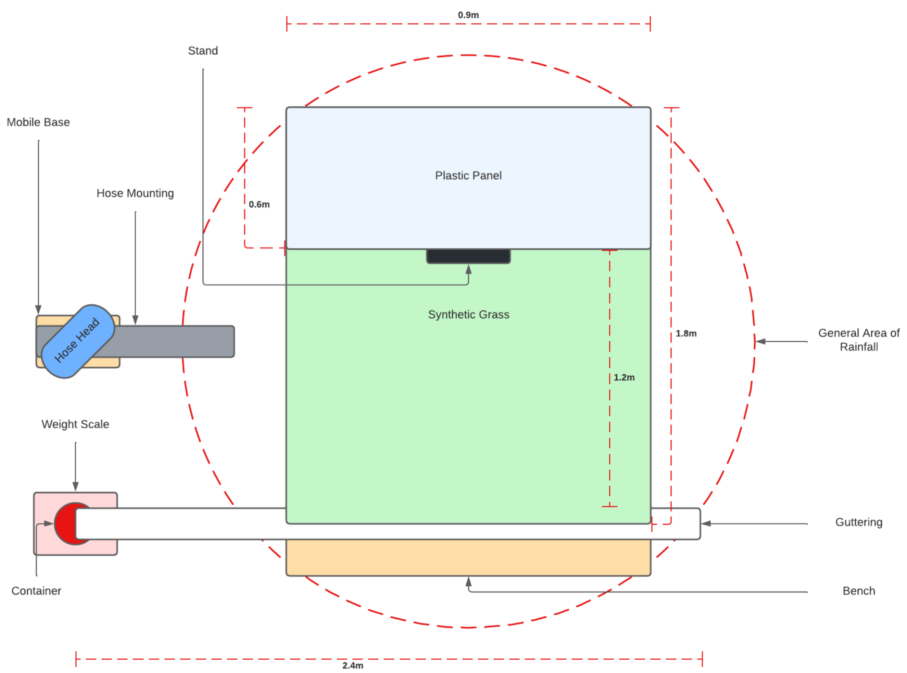


Figure 3.1: Overhead View

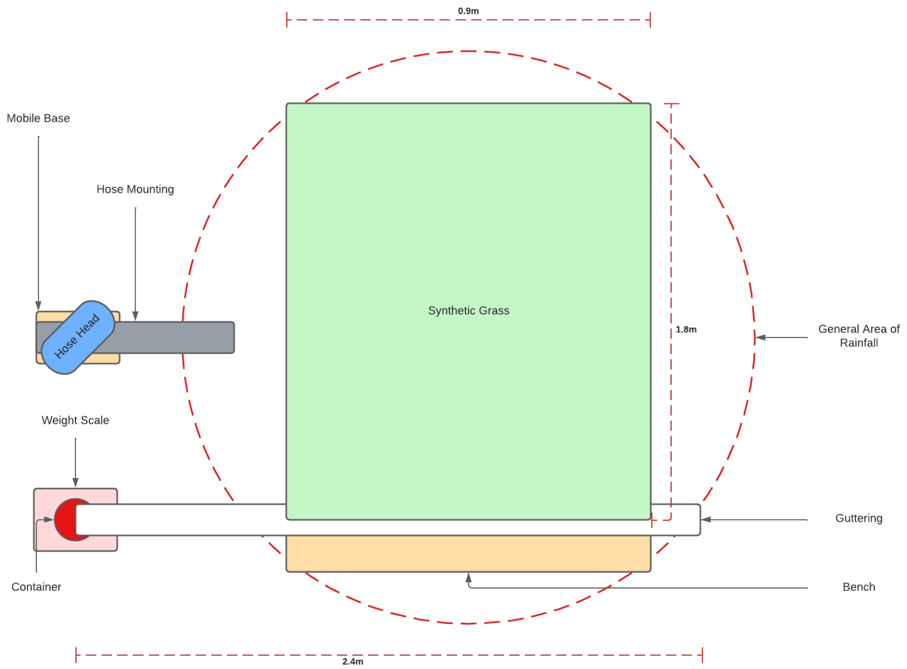


Figure 3.2: Setup without Panel - Overhead View

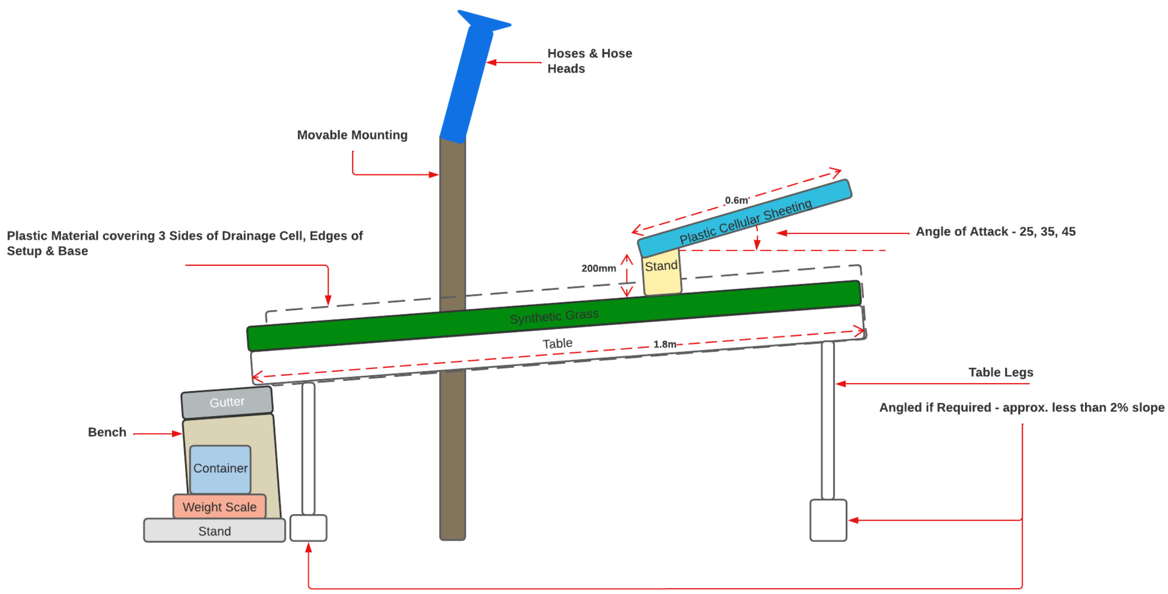


Figure 3.3: Side View

3.6 Experimental Steps

3.6.1 General Setup & Determining Rainfall Intensity

1. Setup equipment as shown within Figure 3.2 in Section 3.5, '*Equipment Setup*'.

2. Place the container in place of where the plastic cellular sheeting will sit, under the water

falling.

3. Turn on tap.
4. Simultaneously start the stopwatch measuring 1 minute.
5. Stop water flow.
6. Measure height of the water in the measuring containers using a tape measure or measuring container markings, in millimeters. (If measurements are inaccurate or water level is too low allow water to flow for another minute and divide the measured water height by the number of minutes, water intensity = water height (mm)/minutes of water fall).
7. Repeat steps until desired intensity of 1.048mm/min is obtained.

3.6.2 Experimental Steps for No Panel Case

1. Setup equipment as shown within Figure 3.2 in Section 3.5, '*Equipment Setup*'.
2. Return container back onto the weight scale as shown in Figure 3.1 in Section 3.5, '*Equipment Setup*'.
3. Turn on tap.
4. Simultaneously start the stopwatch measuring 5 minutes.
5. Measure and record the weight of the water in the container every 15 seconds, using a weight scale and record results.
6. Stop water flow.
7. Continue to measure the water weight in the container on the weight scale every 15 seconds for another 5 minutes and record results.

3.6.3 Experimental Steps for Varying Angles

1. Setup equipment as shown within Figure 3.1 in Section 3.5, '*Equipment Setup*'.
2. Set the tilt angle of the panel to 25° using the level and protractor measuring from a horizontal plane.
3. Turn on tap.
4. Saturate synthetic grass and setup for 1 minute, then turn off tap.
5. Turn on tap.
6. Simultaneously start the stopwatch measuring 5 minutes.

7. Measure and record the weight of the water in the container every 15 seconds, using a weight scale and record results.
8. Stop water flow.
9. Continue to measure the water weight in the container on the weight scale every 15 seconds for another 5 minutes and record results.
10. Repeat steps 2-9 for angles 35° and 45°.

4 Results

4.1 Raw Data

The surface run-off was measured in weight during the experiment and then was converted to volume. The raw data from scale reading can be seen in Appendix C.

4.2 Total Runoff for No Solar Panel Case w/o Edge Guards

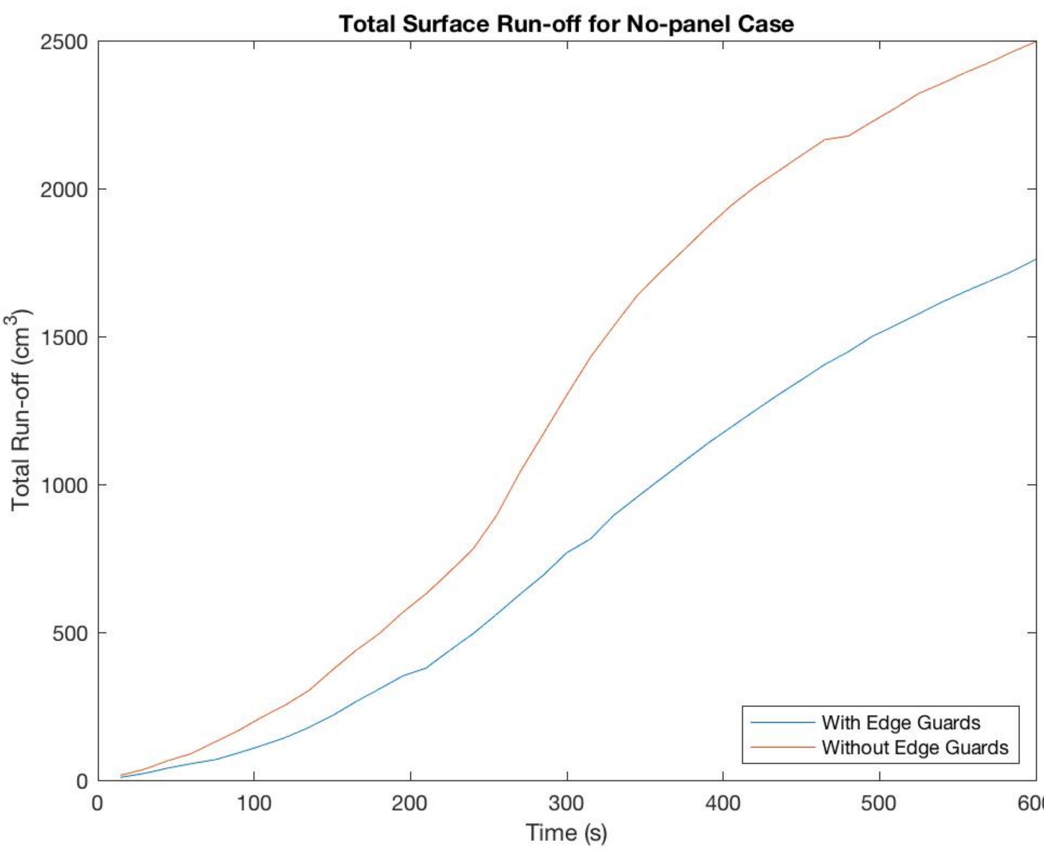


Figure 4.1: Total Runoff for No Solar Panel Case w/o Edge Guards

4.3 Investigation on the Impact of Edge Guards

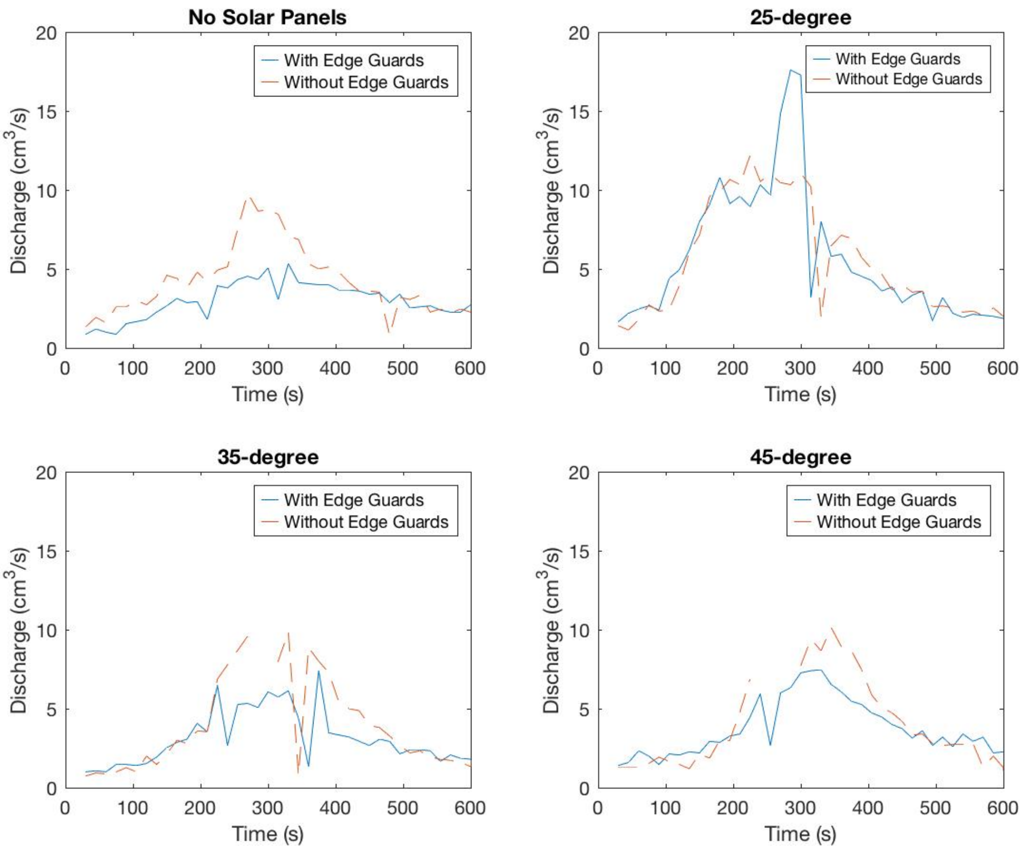


Figure 4.2: Impact of Edge Guards for Different Solar Angle Cases

4.4 Investigation on the Impact of Solar Panel Angles

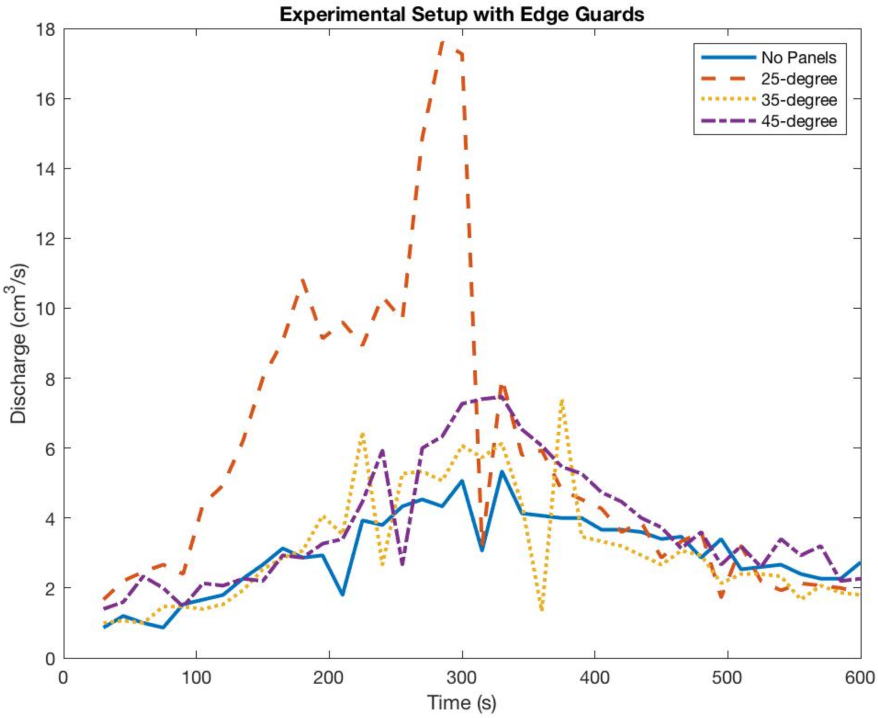


Figure 4.3: Discharge (cm^3/s) vs Time (s) with Edge Guards

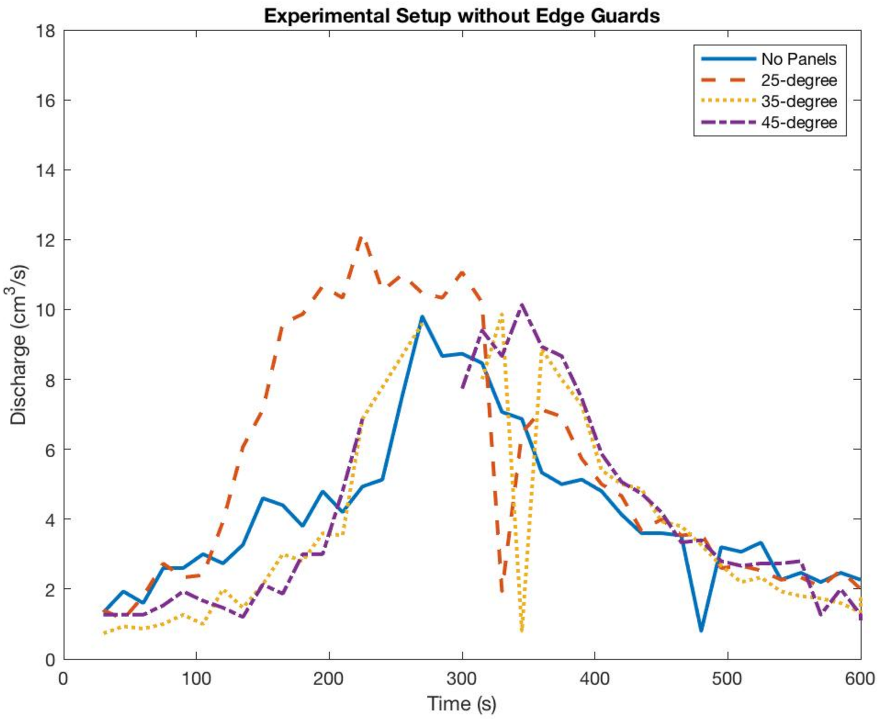


Figure 4.4: Discharge (cm^3/s) vs Time (s) without Edge Guards

5 Discussion

5.1 Evolution of Setup

Over the process of designing the experiment a number of changes were made to its setup. For the original setup the grass was sloped on the short distance, the grass was placed on a drainage cell, the panel was a larger 0.6 by 1.2 metres and covered almost half of the apparatus, the flow rate was to be measured by measuring the milliliters in the measuring container, and a shower hose head was to be used. Upon obtaining more information from the client a second shower hose head was added to ensure full coverage of the apparatus, and the method of measuring the flow rate was changed to be measured in grams on a measuring scale. This was to improve the accuracy of measurement, as most sufficiently large measuring containers are not able to be used to measure accurately to the millimetre, and issues of viscose concavity would be avoided. This setup can be seen below in Figure 5.1 and Figure 5.2.

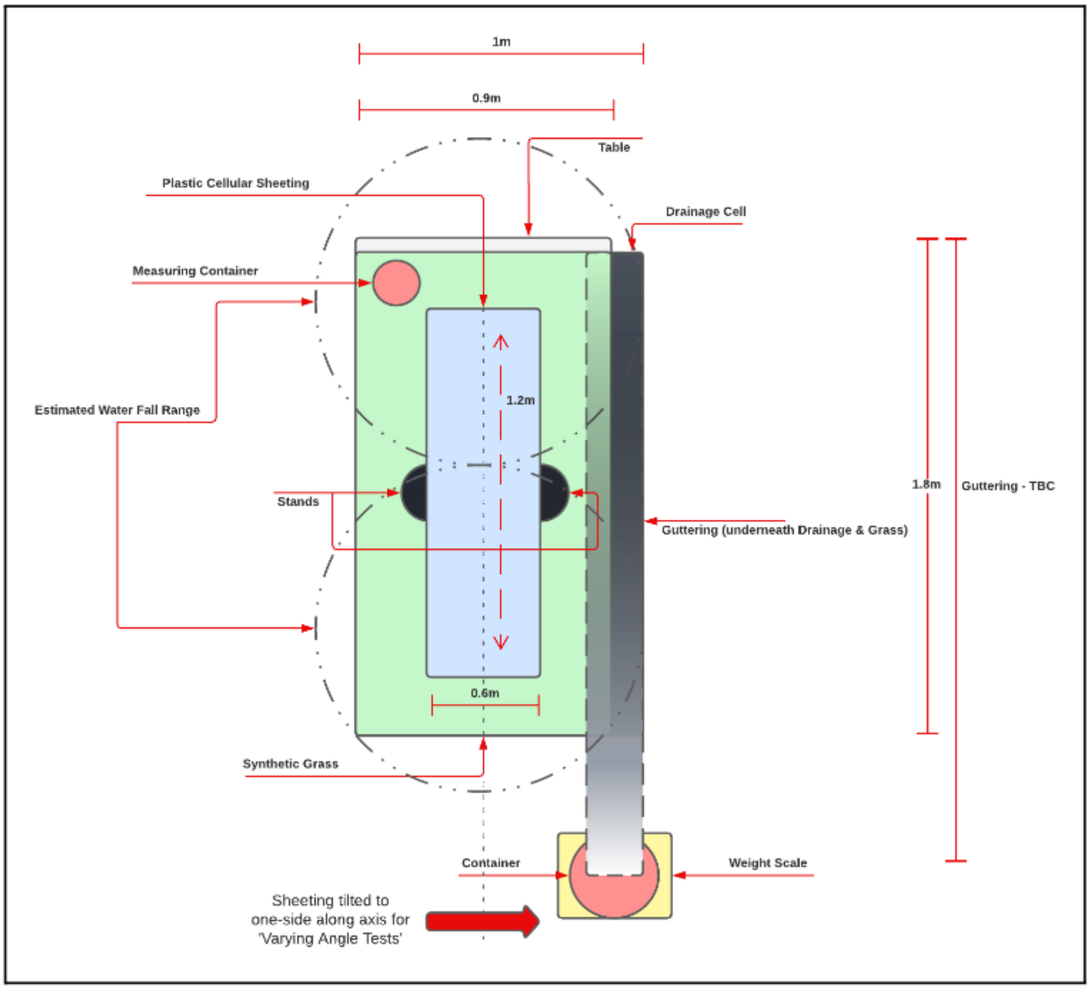


Figure 5.1: Overhead View

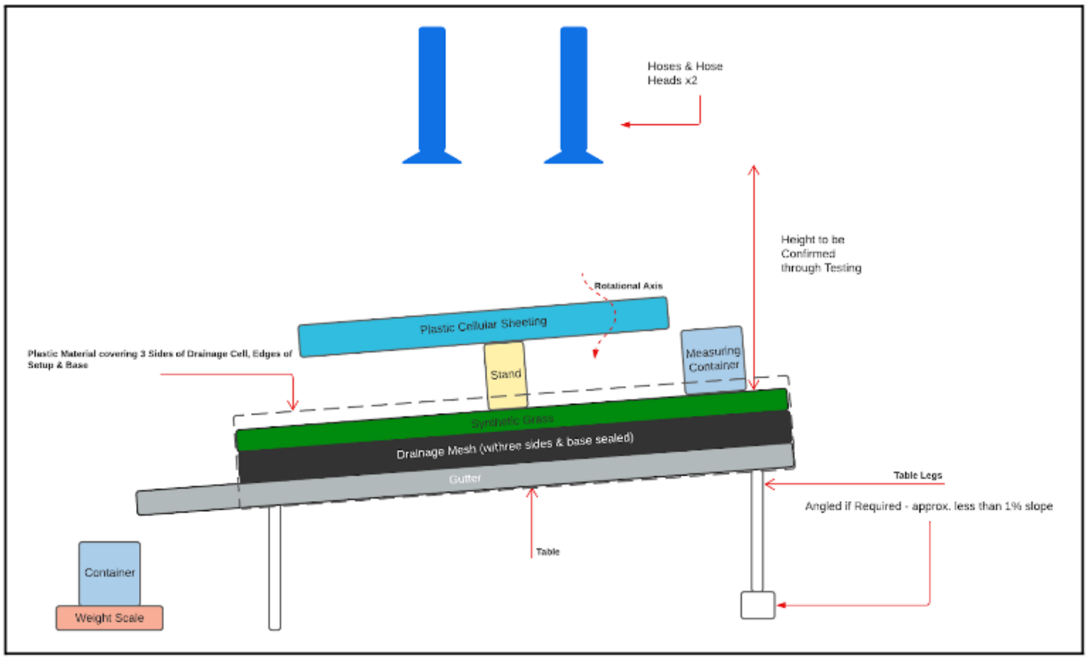


Figure 5.2: Side View

After further information from the client, the orientation of the grass was changed to slope on the long distance, the panel was cut down to 0.6 by 0.9 metres and its position was changed to the top of the grass, and the drainage cell was removed, as the purpose of the experiment was to test runoff. After initial testing stakes were placed under the sides of the apparatus to be used as edge guards and the under sheet was clipped up to prevent water flowing over the side. The two shower hose heads were initially placed next to each other on a gutter above the apparatus, however they were not able to get full coverage of setup. As a result they were moved further apart from one another. After further testing, the overhead shower hose heads proved to be providing far too great an intensity; they were initially replaced by two mist hose heads mounted on a stake, pointing horizontally at the apparatus. However, the intensity was still too great and coverage was poor and the two mist hose heads were replaced by a single cone hose head. The angle of the hose head was adjusted until good even coverage could be obtained at the correct intensity.

As the stakes were now being used to mount the hose head, tiles were placed under the sides of the apparatus to be used as edge guards to prevent water overflowing. A significant problem that arose during testing was that most of the water flowed through the grass onto the plastic sheet. This problem was rectified by sealing the holes in the grass with liquid nails, which significantly decreased the amount of water flowing through the grass. The final setup can be seen in figures 5.3 and 5.4 below. The grass was kept saturated throughout the experiment. The reasoning for this was in keeping the consistency between tests the same, as drying the grass would require something to dry it, such as a leaf blower, and would have to be dried to the same amount between each test. By keeping the grass saturated throughout the experiment, the change in saturation could be keep as low as possible, with little difficulty.

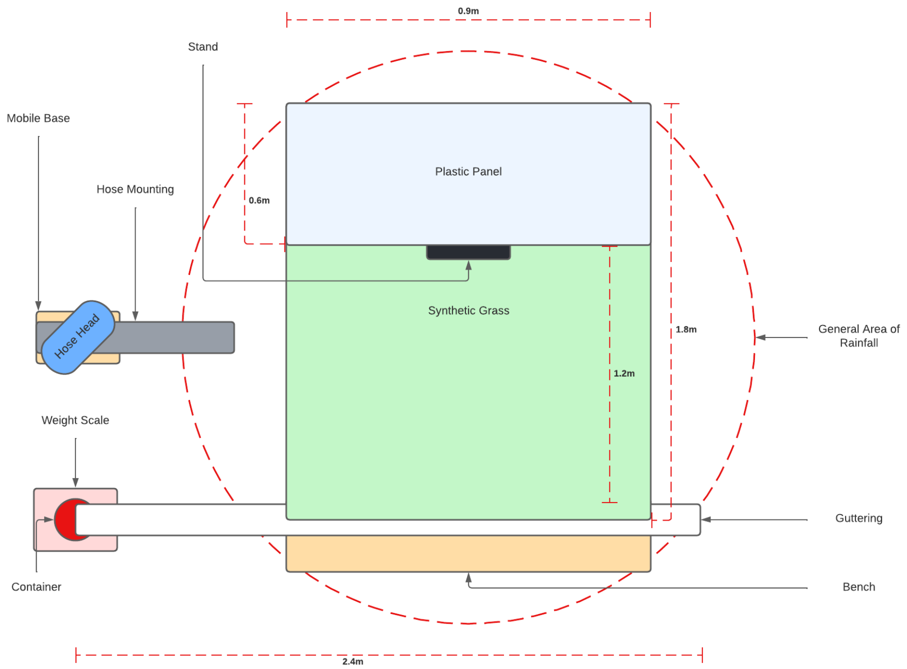


Figure 5.3: Overhead View

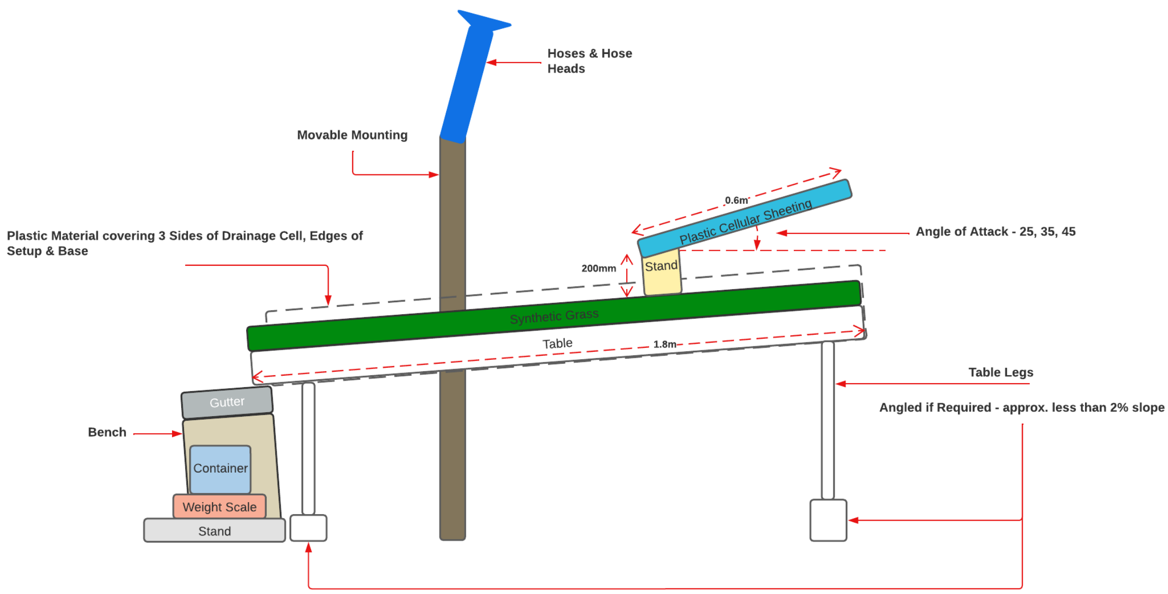


Figure 5.4: Side View

5.2 Validity & Accuracy

The accuracy of the experiment was limited to the experimental setup restrictions based on location and tools/equipment available within proposed budget. Regarding the setup of the equipment and orientation of materials, the accuracy was limited to millimeters.

This is specifically relating to the placement, orientation and resizing of the panel, grass, container for intensity calculation and underside grass mat sealing. These measurements were kept to an appropriate and accurate degree through multiple measurements using both meter long rulers and different measuring tapes for purposes of crosschecking.

Regarding the measurement of the result, accuracy was limited to the unit reading of grams or milliliters. This is specifically relating to the water flow and collection of water in a container weighed on an electronic weight scale. The scale was always calibrated to zero and tared prior to the commencement of water flow or the start of the tests. Furthermore, the time intervals between recording data as well as the total run-time of each test was restricted to an accuracy of milliseconds using an electronic stopwatch. However, due to human reaction and utilizing a manual method of recording data, realistically the accuracy of time measurements were restricted to the nearest second. The timer was always zeroed or reset prior to commencing a test and an electronic time was utilized to eliminate the possibility of inaccuracies or mechanical malfunctions in comparison with analog timers. The angle of the panel and slant of the table was measured using a protractor and level with an attached ruler correct to the nearest whole degree. An accurate reading was obtained by utilizing a flat base aligned to the protractor close to the panel enabling an apex or zero angle to be relatively accurately read upon each adjustment made to the panels angle. The rainfall intensity was accurate to the nearest millimeter per minute utilizing the weight scale and a different dry container. The rainfall intensity was also kept reasonably accurate between tests as when the desirable intensity was determined, the hose head was locked into place using a plastic mounting and head adjustment.

Therefore, within future experimentation it would be effective and viable to utilize equipment to a higher degree of accuracy or units of measurement. An electronic timer correct to milliseconds can continue to be utilized but can be linked to an automated database that records the scale weight, allowing for accurately consistent readings comparative between tests. Furthermore, an electronic protractor would allow for a more accurate calculation of the panel angle. An electronic weight scale that is accurate to grams, however, has a larger weight limit would be recommended as this would enable a larger container to be utilized for tests but also allow units to remain in grams. The water intensity control in future experiments could be more electronically or automatically set via using digital valves or electronically calibrate values. Furthermore, time intervals of water flow or water weight could be reduced if automated and digital hardware is utilized allowing for more comprehensive and accurate results.

5.3 Reliability & Precision

The reliability of the experiment was addressed by implementing measures upon the physical setting which aims to reduce human errors and random errors. All measurements of time and the utilization of the timer and callouts from the timer are made by the same individual to keep a level of consistency of any possible resulting error sources. Most prominent source of error was the influence of wind and weather upon the setup. The wind would have affected the reliability of data as rain droplets and intensity across the setup would have been inconsistent or within a range rather than one uniform intensity over the entirety of the setup. The same electronic timer and scale was utilized to further reduce any random errors that can arise from inconsistencies on equipment calibration or performance. Human error was further reduced by employing the same individuals to record results and fixate/mount the guttering and equipment to deter any human influence when a test commences. The rainfall intensity was calculated prior to commencing any tests hence, reliable consistency of intensity readings was assumed between tests as the hose head and adjustment was locked into place. Furthermore, the valve was sealed using heat and compression to reduce leakages. The set of tests was repeated twice to account for any outliers or errors that may have occurred over a test.

There are various aspects of the experimental setup could not have been entirely controlled and therefore, would have affected the precision of the measurements made. The weather conditions, specifically wind factor was minimized as best as possible by carrying out the tests during low velocity wind times during the day, however, wind was still existent and influencing the intensity of the rainfall and spread over the setup. As the weight data recording was completed by hand and the starting/stopping of rainfall as well as synchronization between the recorder and timer is all influenced or controlled by people, some human error (+/- 3 seconds) can be evident in the run-times of each experiment. Therefore, in future tests the utilization of digital or laser recording tools or hardware can eliminate the human influence on the tests and have a more consistent reading of time. The panel and stand have some small sections whereby minute amounts of water can be restricted therefore, in future investigation a stand that is reflective more of a real solar panel stand should be utilized.

5.4 Scaling

In terms of scaling the apparatus was scaled to roughly one quarter of the size of the typical section of a solar farm. On the modal the panel was exactly 0.6 m long and distance between panels was 1.2 m long, a perfect 1:2 ratio. In reality panels vary from 2.172 m to 2.285 m long, while the distance between panels vary from 4.715 m to 5 m long, as can be seen in Figures 5.5 and 5.6, a ratio just under 1:2 [7]. However these differences were variable and negligible. For the modal the H_min was 0.2 m high, while in reality H_min varies from 1.07 m to 1.37 m high, a scale of just under 1:5 [7].

Wagga North			
panel length	L	2.182	m
distance between panels	d	5	m
Total length	D	7.182	m
pile height	h_min	1.07	m
	h_max	1.44	m
West Wyalong			
panel length	L	2.285	m
distance between panels	d	4.715	m
Total length	D	7	m
pile height	h_min	1.37	m
	h_max	1.52	m
Wyalong			
panel length	L	2.172	m
distance between panels	d	4.828	m
Total length	D	7	m
pile height	h_min	1.15	m
	h_max	1.35	m

Figure 5.5: RBG Solar Farm Data [7]

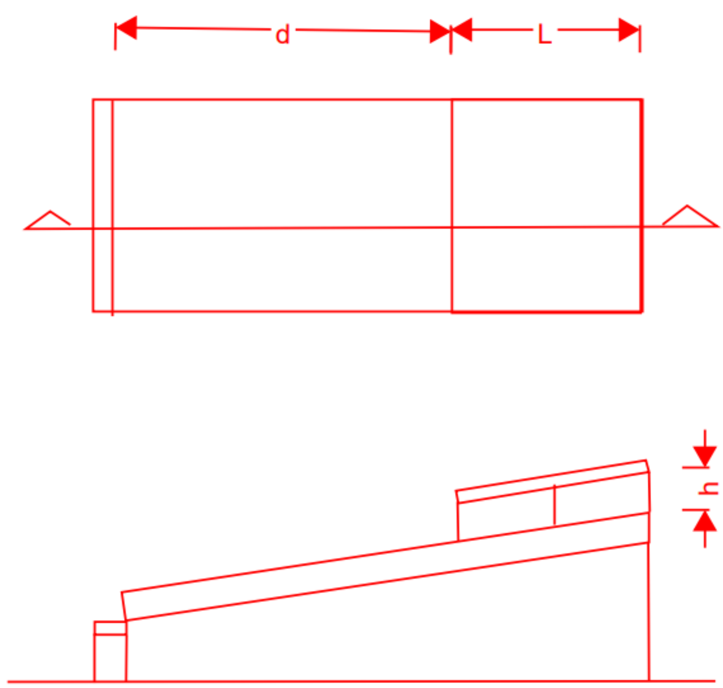


Figure 5.6: RBG Solar Farm Diagram [7]

5.5 Weather Conditions

The weather conditions at the testing site were estimated by taking the average of nearby weather stations from the bureau of meteorology. the full data can be seen in Appendix A.

Date/Time EST	Temp °C	App Temp °C	Dew Point °C	Rel Hum %	Delta-T °C	Wind				
						Dir	Spd km/h	Gust km/h	Spd kts	Gust kts
18/04:3	12.425	8.175	-0.65	40.5	5.35	WSW	11.5	18.5	6.25	10
18/04:0	13.1	8.625	-0.9	38	5.7	WSW	12.5	19.75	6.75	10.75
18/03:3	13.55	8.875	-0.4	38.25	5.775	WSW	14	22.5	7.5	12.25
18/03:0	13.65	8.275	-0.725	37.25	5.9	WSW	17.25	30	9.25	16
18/02:3	14.025	8.325	-1	35.75	6.15	WSW	18.75	29.75	10	16
18/02:0	14.05	8.55	-0.7	36.25	6.1	WSW	18	30.75	9.75	16.5

Figure 5.7: Estimated Site Weather

5.6 Discussion of Results

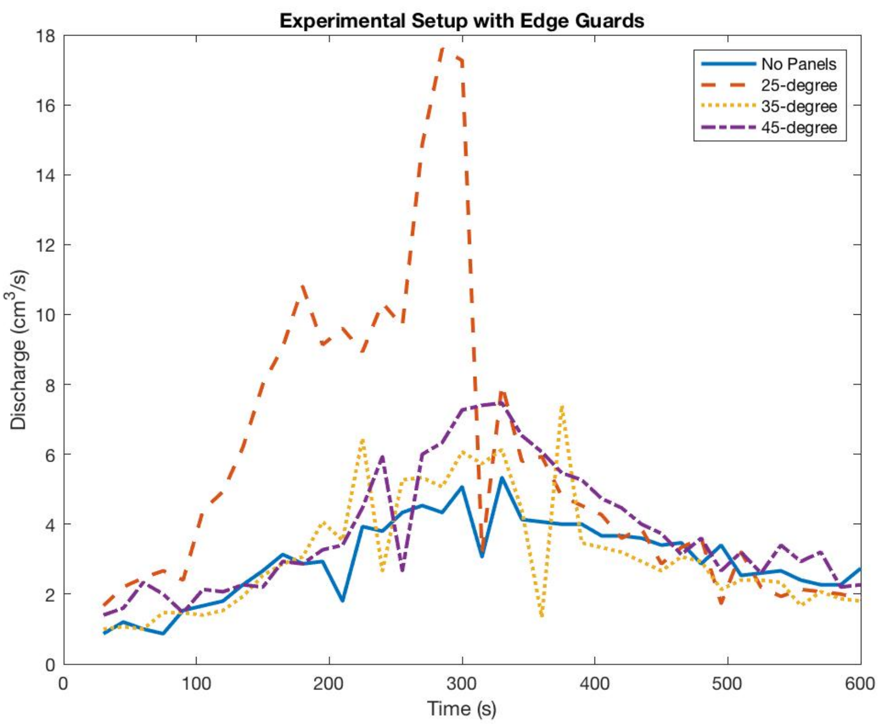


Figure 5.8: Discharge (cm^3/s) vs Time (s) with Edge Guards

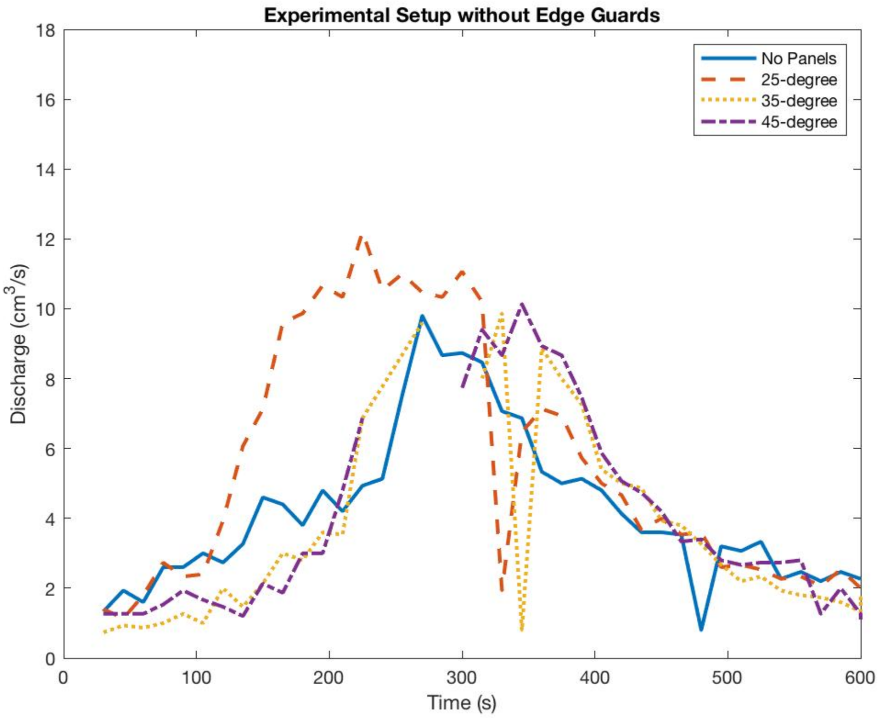


Figure 5.9: Discharge (cm^3/s) vs Time (s) without Edge Guards

Both graphs (Figure 5.8 and Figure 5.9) show that surface runoff has no significant increase when comparing 35° and 45° cases with no panel case.

Both graphs shows that water flow reached its peak more quickly and there is increased surface runoff when comparing the panel at 25° case to no panel case.

The graph without the edge guard setup shows that the water flow reaches the peak more quickly with a shallower angle.

To explain the results, the two effects associated with changing panel's angle are discussed in the following:

1. Panel Catchment Area

Changing the panel angle (slope) would also changes the panel catchment area* and in turns changes the flow velocity due to water travelling on different surface (with different surface roughness ratio between panel and grass).

*The panel catchment area is the area of the grass that does not have direct exposure to the rainfall because of the panel in place. i.e the projection area of the panel to the grass.

Assuming the rainfall coming down vertically, the 25° panel has more panel catchment area compared to the 45° panel and thus more volume of runoff generated directly by the panel. Water flows on the panel has a lower surface roughness compared to grass and it leads to quicker and more surface runoff when there are more runoff from the panel.

Panel width (m)	total grass length (m)	
0.6	1.8	
cases	projected distance (m)	panel catchment to total catchment (%)
no panel	na	0%
90	0.00	0.0%
85	0.05	2.9%
80	0.10	5.8%
75	0.16	8.6%
70	0.21	11.4%
65	0.25	14.1%
60	0.30	16.7%
55	0.34	19.1%
50	0.39	21.4%
45	0.42	23.6%
40	0.46	25.5%
35	0.49	27.3%
30	0.52	28.9%
25	0.54	30.2%
20	0.56	31.3%
15	0.58	32.2%
10	0.59	32.8%
5	0.60	33.2%
0	0.60	33.3%

Figure 5.10: Panels Catchment Percentage

The figure above shows the percentage of the panel catchment to the total catchment for various angles. For 25°, it is about 30% and for 45°, it is about 24%.

For why the surface runoff does not show much difference when comparing the 35°,45° cases to the no panel case and why there is a delay to peak flow with steeper angle, the panel interference is discussed in the following.

2. Panel Interference

Since the panel is wide and rain comes at all different angle, panel in place would slows down and block some rainfall (especially rains from the back of panel).

For 35° and 45° panels, although there are some direct runoff from the panel, the panel itself could also slowdown and decrease runoff, and the level of interference might depend on the panel's angle.

Considering rainfall direction only from the back of the panel, a 90° panel is the most effective block to the rain. A 45° panel is a more effective block than a 35° panel, and a 35° panel is a more effective block than a 25° panel.

It is possible that the panel with a steeper angle has more interference to the rainfall which leads to slower runoff.

It is also possible that the panel catchment to total catchment percentage has to hit at least 30% so that enough runoff from the panel can overcome the loss of runoff from interference of the panel and make an increase in total.

The following figure shows the further investigation required to verify the above explanations.

Angles	Investigation Reasons	Why this angle/details
90 (vertical)	- see if interference exist and decreases runoff	- presumably has most interference
25	- see if 25 degree slope itself makes difference in runoff	- concluded 25-degree panel has considerable effect but unsure of the critical variable - change the panel catchment to total catchment percentage to ~23.6% by using a longer grass, and compare to the 45-degree curve and no-panel curve from original dimensions
various	- see if 30% "catchment percentage" is a hurdle to increase surface runoff	- keep the same 30% "catchment percentage" and change the angle compared to no-panel case
0-5 (horizontal)	- see if no slope increase runoff	- solar panel angle in extreme wind event - make sure water on panel flow in one direction
60	- see if it changes runoff	- solar panel night-time angle - can use same set-up

Figure 5.11: Further investigation

5.7 Improvements

As an evaluation of the experiments performance, the following section includes recommended future measures that would be beneficial to more accurately and reliably accomplishing the aim of the experiment. The overall improvements can be summarised in the following list:

- Weather - Wind Conditions
- Consistent Rainfall Coverage
- Consistent Saturation
- Synthetic Grass - Density, Length & Infiltration
- Secure & Update Apparatus

The most important improvement to implement and consequentially collect a more reliable set of results when performing the investigation in future is carrying out tests under better weather conditions. Due to limited time and bad weather over the duration of the project, specifically on the planned dates and location of 11-15th of July 2022 within the area of Edmondson Park, the experiment was forced to be carried out on the 10th of July as weather was progressively descending into rain, flooding and storming which would disrupt the outdoor setup. Therefore, in future tests, two solutions can be proposed:

1. A closed, indoor laboratory setup if wind as a variable is desired to be eliminated.
2. An outdoor setup similar to this investigation however, performed on a calm day through coordinating with weather & meteorology reports.

Either solution ideally negates wind in the tests, therefore, a rain or storm is being modelled without wind and hence, deeming the model either way less realistic. However, removing the wind factor would still allow for results collected to be valid in regard to the aim of investigating runoff effect of solar panels.

Partially accomplished in this experiment and critical for future is pre-saturation of grass. This would involve maintaining a standard consistent point of wetness to the setup prior to commencing a test and is simpler and less time consuming than drying the setup between tests. Therefore, in future tests it is recommended to have a **minute** of saturation in-between tests before commencing the 10 minutes of data collection and readings.

Rainfall coverage is also an aspect that has been evident to influence the rainfall and is an aspect influenced by the wind conditions. Utilising a secondary container on the grass (somewhere on one of the corners of the table) can allow participants to keep track of consistency between tests in terms of total rainfall and intensity onto the setup.

Using a synthetic grass that is more reflective of the taller grass on solar farms would allow for results to reflect or incorporate findings with regard to the retarding effect. Furthermore, having a taller grass length will allow greater intensities of rainfall to be investigated as the setup would be able to accommodate a greater amount or collection of water prior to the point of flooding (water level arising above the height of grass or submerging the grass entirely).

Data would have a greater extent of accuracy by using a bigger scale that can accommodate a larger bucket however, the scale desirable would be required to remain in the same degree of measurement (grams). Utilisation of an electronic, laser and/or automated logging system would be most effective in collating data. This would remove human errors and influence. The system could also operate with a computer whereby the readings are automatically logged onto a database.

Panel Position

The current panel position in the experimental setup is at the top-end of the apparatus. Reasoning for this is to model a scale cut section of a repeating larger solar farm to have results obtained translate to the practical environment. Further details on scaling is available under section *5.4 Scaling*. Below this cut section motivation can be visualised within the figure:

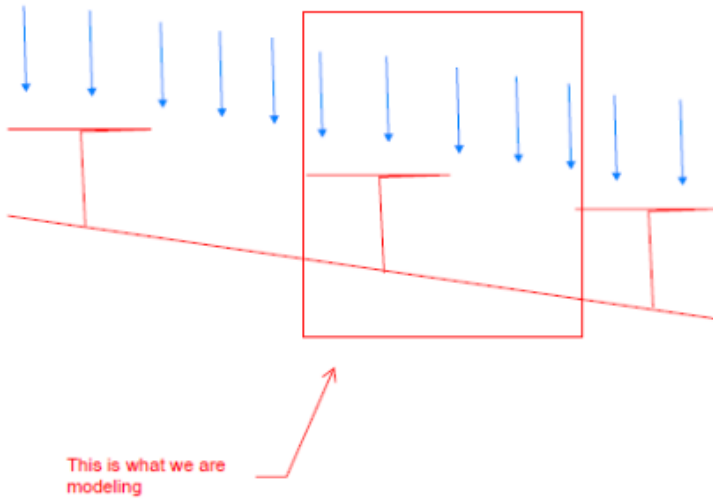


Figure 5.12: Cut Section of Solar Array Visualised

To tackle the issue of rainfall coverage and wind effects in an outdoor setup, there are two proposed solutions within this investigation - both can be employed to further improve or control the investigations variables:

1. Panel positioned in the middle rather than the top to increase the catchment of water on the panel, therefore, adjusting the setup to be concentrated further on the original aim.

2. Increase the horizontal length or span of the panel to also increase panel rainfall catchment and tackle the rainfall swirling effect.

Such improvements would also allow for a distinctive conclusion to be drawn regarding edge guarding and the impact it has upon the tests. This would tackle the discrepancies in results where differences are significant. In conclusion panel placement now becomes an important factor in the investigation.

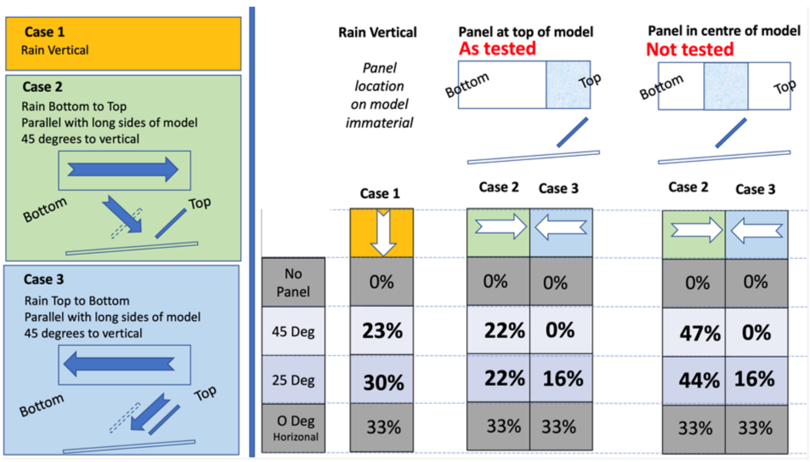


Figure 5.13: Panel Catchment as a Percentage of Total Catchment

The figure above quantifies the percentage of water being caught by the panel using geometry and calculating the panel shade. With our aim of investigating runoff behaviour due to the panel, a higher catchment in the setup would be desirable.

The first column denotes perfect vertical rainfall, the next denotes left and right rainfall swirling case in the setup tested (panel placed at the top end of apparatus) and the final column denotes the same rainfall swirling case with a setup of the panel centralised in the model. The last two columns denote a comparison between the two placements of the panel and the central placement of the panel potentially being more desirable in this investigation.

6 Conclusion

In conclusion, the experimental investigation was successful in highlighting the requirement for further future tests due to previously unforeseen and unexpected variables - some of which require reevaluation from all parties involved to determine the best route for proceeding and investigating the established experimental aim. The results have denoted that the panel does have an effect on rainfall runoff however, which angles make the most significant impact and intuitive trends have not yet been fully established or confirmed through evidence.

6.1 Future Work

The investigation was unsuccessful in giving a decisive response to the aims laid out. Therefore, future works recommended include further tests that implement the improvements suggested under Section 5.7, *Improvements*. The scope of this investigation can also be extended to investigate aspects such as special cases of categorised storm events, the specific influence of wind and differing wind conditions, placement and arrangements of panels on the grass and differing grass conditions.

7 Pavement Background

Within solar arrays and solar farm sites across the world, post construction traffic conditions are generally extremely light resulting in the pre-existing pavement or road system designed to be conservative. Therefore, to optimize the values of an organization and the overall costs-benefits, alternative market products in the form of geosynthetic material are potentially viable options to reduce future costs and sustainability demands on solar arrays. This report section aims to highlight, investigate, and propose suitable product types that can substitute conventional pavement design on solar farms through comparisons of benefits and costs.

7.1 Solar Farms Relevancy

During the construction phase of a solar farm, heavy vehicles are used for foundational work and the installation of polls and panels. The maximum expected vehicle load is 44 tones, with a maximum load per axle of 16 tones [6]. Once construction has finished however, most maintenance vehicles using the roads will be much lighter. The roads must be compliant with rural NSW fire requirements including the NSW RFS Design Criteria as seen in Figure 7.1 [6] and the minimum curve radius as seen in Figure 7.2 [8]. While it is important for the roads to meet all these requirements, it is also important to keep building and maintenance costs as low as possible and to make them as environmentally sustainable as possible.

NSW RFS Design Criteria		
Parameter	**Criteria Adopted**	**Reference**
APZ Zone	A minimum 15m APZ for the structures and associated buildings/infrastructure. The APZ shall be in accordance with the NSW RFS Standards and must be maintained to the standard of an IPA for the life of the development.	NSW Rural Fire Service, Planning for Bushfire protection guide (2019). Section 8.3.5. 10m noted as minimum. Site has an additional requirement.
APZ Zone – Property Access	Maximum grades and crossfall do not exceed 10 degrees.	NSW Rural Fire Service, Planning for Bushfire protection guide (2019). Table 5b
Internal Roadways /Property Access	Internal access roads and emergency access easements to be provided to ensure that a maximum 150m hose reach length to all site regions is achieved and a desirable maximum of 60m hose reach length is achieved.	Correspondence and Direction

Figure 7.1: NSW Roads Design Criteria [6]

Curve radius (inside edge in metres)	Swept path (metres width)
< 40	4.0
40 - 69	3.0
70 - 100	2.7
> 100	2.5

Figure 7.2: Curvature Requirement [8]

8 Conventional Pavement Solutions

8.1 Asphalt

Within the conditions of the solar farm, the asphalt pavement will be able to accomplish the requirements of carrying lighter vehicles; however, factors such as sizing, and layering may affect the feasibility of employing this material/solution. The purpose of asphalt paving in general would be (in this case) to cope with the low frequency of vehicles that would visit the solar farm however, some in case of panel damages and need to repair or deliver larger panels, heavy vehicles may need to travel through the array.

The limitations of asphalt include the limited lifespan in comparison with other materials such as concrete. In comparison with other products and solutions on the market, asphalt also has a reasonably high maintenance and therefore, comparatively higher cost.

Introduction

Asphalt pavements within solar arrays can be a solution to cope with the lighter traffic conditions post-construction. Asphalt pavements consist of rock and sand combined with asphalt cement to hold the structure together. The combination determines the structure and strength of the pavement.

Purpose

Within the conditions of the solar farm, the asphalt pavement will be able to accomplish the requirements of carrying lighter vehicles however, factors such as sizing, and layering may affect the feasibility of employing this material/solution. The purpose of asphalt paving in general would be (in this case) to cope with the low frequency of vehicles that would visit the solar farm however, some in case of panel damages and need to repair or deliver larger panels, heavy vehicles may need to travel through the array.

Advantages

The primary advantages that asphalt are suitable for lower budgeting, easy to install and implement, fully recyclable, minimal reparation processors and has a long life-time. Therefore, replacing a surface or building a new pavement from asphalt can prove to be more cost-effective. Furthermore, designated walkways and carports can be extended to the asphalt in forms of patterned border, cobblestone edging, ground lighting and similar structures.

Costs

In comparison with cement, re-blacktopping asphalt is cheaper and quicker. This is primarily due to the lack of requiring excavation, clearing the surface, and laying down new foundations in reparations.

Contractors' transportation cost must be factored into overall budgeting as closer range contractors or suppliers can significantly affect resulting rates.

As for the average rates per square meter of asphalt, the following table documents prices across Australia by state:

Table 8.1: Average Cost p/Square Meter by State

State	Cost ($AUD)
NSW	45
VIC	40
QLD	40
SA	30
WA	25
NT	30-40

In comparison with cement, the average-sized pavement can cost anywhere between $65 to $150 per square meter. The cheapest of cement options are often still more expensive in comparison with asphalt.

The cost of the asphalt material itself is calculated via the mix which can be quoted from contractors. The required information is typically:

- Selection of design
  - Color
  - Kerbing
  - Soak wells & drainage
  - Connections & pavement crossovers
  - Line markings
- Size of area
- Assessment of existing surface
  - Gravel surfaces typically do not require excavation work – the surface is leveled, and any holes filled. A new layer of hot mix asphalt can then be laid over.

Cost can be reduced by using higher quality asphalt as this would be most resistant to damages and extend the longevity of the material. Hence, a reduction in future reparations and maintenance work [9].

Feasibility

Asphalt is often required for larger areas and for the sake of affordability it is recommended that utilization of asphalt be for sites larger than 150 square metres. Time of vehicle upon asphalt will also affect the feasibility of such a solution on solar arrays. The longer a maintenance or heavy vehicle sits on asphalt, the greater the pressure generation. To combat the pressure effects, base and asphalt layers thickness would require increase. Contractors would assess the stiffness of the material and recommend asphalt that can be more durable under the weight of heavy vehicles.

Using data of common state regulated asphalt road designs on rural areas, an estimate of the proposed thickness of asphalt can be approximately determined. The recommended thickness of the pavement in conjunction with investigations off other rural preexisting asphalt roads are as follows:

Table 8.2: Estimated Granular Pavement Thickness

Arterial Road Types	Design Traffic Load (MESA/Lane	t(min) (mm)	t (mm)
FWY Rural	28.3	150	500
Major HWY Rural	5.4	150	460
Other HWY Rural	1.0	150	410

8.1.1 Spray Seal

Spray seal is a more basic form of pavement/road generation designed for light traffic conditions utilising a single layer of bitumen. Spray seal is hot liquid applied via spraying along with a following application of crushed aggregate - single layer.

Advantages

Advantages of utilising spray seal are as follows:

- Less Heating
- Reduced use of Cutter Oils in Cooler Conditions
- Improved Adhesion to Damp Surfaces

Disadvantages

Disadvantages of utilising spray seal are as follows:

- Higher Cost
- Slower Rate of Strength Gain
- Increased Time to Seal

Contractors

- OzPave
- Active Asphalt
- Boral Asphalt

8.2 Gravel

Introduction Gravel is a loose aggregation of different size of the rocks, sands, and some clay. According to Udden-Wentworth scale, the size of gravel has been scaled into two categories, including granular gravel (2–4 mm or 0.079–0.157 in) and pebble gravel (4–64 mm or 0.2–2.5 in). In another standard ISO 14688, there are three grades of the gravel: fine, medium, and coarse, with ranges from 2–6.3 mm to 20–63 mm. Normally, gravel weighs about 1,800 kg per cubic [10].

The most popular applications of gravel are pavement construction and concrete resource materials.

Figure 8.1: Gravel

Advantages

In some areas, especially in rural areas, gravel is a popular material of pavement because they are low-cost, efficient drainage and easy to maintain. Compared to other conservative method as asphalt and concrete, gravel is far cheaper especially for the long driveways. Additionally, it can last for up to 100 years with regular maintenance [11].

Disadvantages

Despite all the advantages listed above, there are still some drawbacks about this conservative pavement material.

First of all, the gravel is the allocation of the rocks. Therefore, when there are stormwater or rainfall, the rocks could be washed away easily. Even though it could be fixed by regular maintenance, the time and effort to put on the pavement still needs to be considered. Secondly, the gravel is not suitable for the heavy traffics due to the nature of itself. Having eh heavy traffic on it raises the possibility and frequency of maintenance. The last disadvantages worth mentioning is the dust and road noise [11].

Cost

As mentioned in the introduction part, low-cost is one of the main benefits of gravel. The cost of the gravel pavement could be from $1 to 3$ per square foot. Even compared to some of the new materials, gravel could still be considered as one of the cheapest materials for pavement.

However, the cost of the whole project could be varied depends on two elements. One is how far the client wants the gravel to be and another one is how thick of the gravel client asked

Feasibility The installation of gravel is very easy. An initial pavement of gravel could be installed simply by using the dump truck to unload the crushed rocks. After, ta light motorized machine such as mini track loader could be used to move the gravel to the crushed rocks to form a pavement.

However, there some additional cost that might happen during the construction of the driveway. These steps will increase the life span of the pavement and reduce the frequency and cost on maintenance.

The steps are listed as below:

1. Remove topsoil
2. Compacted the soil below the topsoil.
3. Lay down the optional geotextile fabric.
4. Above the fabric is a 4-inch layer of fist-sized rocks.
5. The next layer above is a 4-inch layer of gravel roughly the size of golf balls.
6. Finally, there is a third layer of marble-sized gravel.

The driveway also is shaped with a crown at the centre so that water flows off to either side. Each layer is compacted thoroughly before the next layer is added.

Contractor

AB contracting

David Boots Sand and Gravel

8.3 Concrete

8.3.1 Introduction

Concrete is a mixture of cement, water, air and gravel. Concrete pavement, which is occasionally called rigid pavement, is a concrete layer that is in contact with traffics directly and it is used for different purposes and applications. The concrete pavements can be modified and changed in various ways as per the requirement. Concrete pavements offer several advantages which is not possessed by bituminous pavement designs, for example, it is considerably suitable for large points loads, withstand diesel spillage and other aggressive materials, suitable for cases where sub-grade strength is low, resist high temperature, and many more benefits [12]. The following section documented advantages and disadvantages of concrete pavement.

8.3.2 Advantages

- Concrete is an extremely durable pavement material ideal for heavy traffic loads.
- Concrete is resilient against extreme Australian weather conditions
- its performance is not compromised by hot weather or fires, nor erode in floods.
- concrete roads reflect up to twice the heat that is absorbed by typical black road surfaces.
- Concrete roads will not shove or vertically rut and are less susceptible to potholes
- Resist impact and abrasion and Petro-Chemical attack.
- **Life-span:** Concrete pavement has a higher life span then other materials such as asphalt and gravel. It is also low maintenance, especially for under tough weather and heavy traffic conditions.

8.3.3 Disadvantages

- Preliminary cost is very high for construction.
- The paving cost is also remarkably high for concrete roads as compared to asphalt roads.
- The concrete roads face greater maintenance issues as when the concrete roads rupture, the entire concrete slab must be substituted.
- In concrete roads, mud pumping issues frequently occur.
- In concrete roads, joints should be filled at regular intermissions.
- Snow is accumulated on concrete roads since snow dissolves quickly on asphalt roads as compared to concrete roads.
- Safety is a great concern in concrete roads as the vehicles are likely to slip or slide owing to rain and snow.

8.3.4 Contractor(s)

- Cement Concrete and Aggregates Australia

9 Alternative Options For Pavement

Currently, there has been an increased use of geosynthetic products which aimed to improve pavement structures through mechanical stabilisation and lifespan. According to the Geosynthetic Materials Association (GMA), commercially available geosynthetics have been identified as eight distinct categories including, geogrids, geomembranes, geosynthetic clay liners, geocomposites, geotextiles, geofoam, erosion control materials and geocells [13].

The following sections documented the selected geosynthetics from the eight categories for pavement design optimisation based on their functions, applications, installation, maintenance, and some of the case studies in which the selected geosynthetic products have been applied in infrastructure projects by many civil engineering firms across Australia.

9.1 Geogrid

Geogrids from Cirtex are manufactured in a facility that has achieved ISO9001 certification and has passed the CE certification. Geogrids are embedded into the ground therefore maintenance is not required. The geogrids are manufactured from polypropylene and polypropylene has an expected design life of not less than over 100 years when not exposed to UV.

9.1.1 Function

Geogrid improves pavement system performance through reinforcement.

Geogird has open structure and large apertures which allows interlocking with base course aggregate and change the stress and strain conditions. Geogird can function as base course lateral restraints. It prevents lateral spreading of aggregate and confine aggregates to increases their strength/stiffness. It also reduces vertical stresses and shear stress on the subgrade [14]. Other functions of geogird includes increased bearing capacity by forcing the potential bearing capacity failure surface to develop along alternate, higher shear strength surfaces and used as membrane support of the wheel loads [14].

9.1.2 Application

DuraGrid X is most commonly used for pavement stabilisation over soft soils and the reinforcement of aggregate in raft foundations. DuraGrid X can also be used as a non-slip grid on boardwalks. (cirtex website)

9.1.3 Sustainability Aspect

The geogrid embedded into ground does not require maintenance. It is estimated to have over 100 years life span when not exposed to UV.

9.1.4 Installation/Maintenance

The following installation procedure is extracted from the Cirtex website.

Before installation the ground surface will need to be prepared to provide a level and uniform surface with all appropriate clearing complete. Additional preparation may be required as advised from your Cirtex representative or project engineer.

Next place the DuraGrid X/GridTex as specified in the project plans and specifications. The geogrid must be laid flat and smooth directly on the prepared subgrade*. All wrinkles and folds need to be removed.

The geogrid should be overlapped with a minimum of 300mm in all directions or joined as specified in the project plans. Soft subgrade installations may require a greater overlap or joining of rolls using cables ties to help maintain the placement and orientation during fill placement.

Consult the projectplans and specifications for more instructions.

Please note that some applications may require additional layers of DuraGrid X. The distance between the layers should not exceed 500mm unless otherwise specified by the project engineer.

*In most applications a nonwoven geotextile such as DuraForce™ AS280 should be installed directly onto the prepared subgrade before laying the DuraGrid X.

9.1.5 case study

Duragrid has been applied to Queenstown International Airport for runway widening. The application of Duragrid was to reinforce the new runway pavement. A layer of DuraGrid was placed directly over the DuraFlow drainage composite to give reinforcement to the pavement [15].

9.2 Geomembranes

9.2.1 Function

Geomembranes are impermeable membranes used with foundation, soil, rock, earth or other geotechnical engineering related materials as an integral part of a project, structure or system [16]. The main purpose of geomembranes is to control fluid migration.

9.2.2 Application

Mechanical properties can vary deeply, the two major categories of geomembranes are flexible and non-flexible/ semi-crystalline [17]. For example HDPE, a semi-crystalline geomembrane, has strain of only around 20%, whereas PVC, a flexible geomembrane, has a strain of just under 500% [17]. Likewise HDPE geomembranes are susceptible to puncture at significantly less pressure than flexible geomembranes [17]. On the other hand, HDPE can take significantly more stress with much less strain then PVC, with HDPE able to take a stress of over 15000 kpa at a strain of

10%, whilst PVC can only take a strain of less than 5000 kpa at a strain of 10%, as see below [17]. Geomembranes are often placed on top of the subgrade and below a geotextile [16, 17].

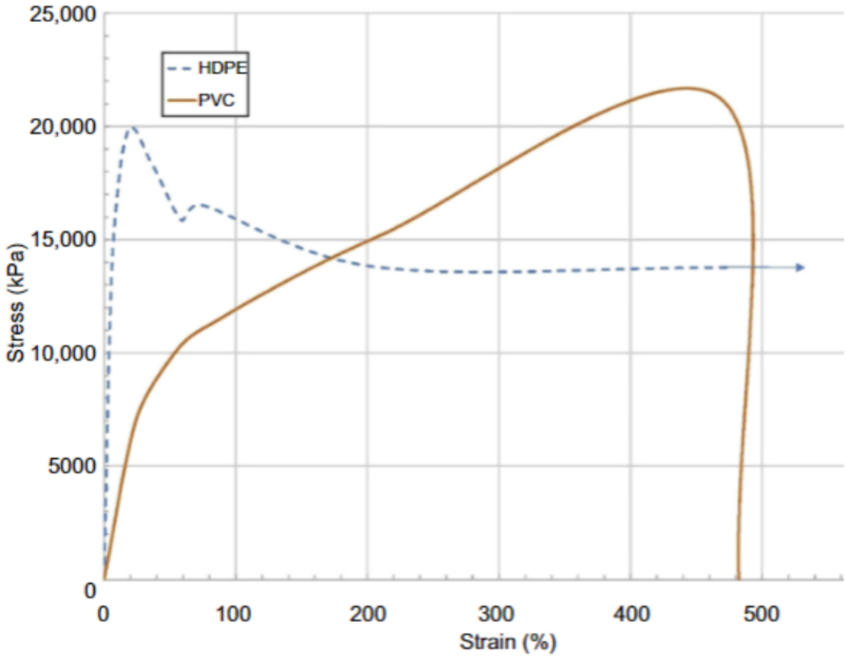


Figure 9.1: Geomembrane Stress Strain [17]

9.2.3 Sustainability Aspect

the lifespan of PVC geomembranes is around 30 years [18] whilst the lifespan of HDPE geomembranes is several hundred years [19].

9.2.4 Installation/Maintenance

Before a geomembrane can be installed, the sub-grade must be completely smoothed, with any potential projections removed [20]. If a build up of gas pressure is possible due to organic decay or the water table, a geomembrane cannot be installed unless there is a slope of at least 1.5% and must be vented at the bottom of the slope [20]. The geomembrane must be anchored in a trench 0.3m wide and 0.6m deep at the top end [20]. The different sheets of the geomembrane are welded together with a welding machine that fuses the two pieces together with upper and lower contour rollers that apply heat and pressure, with the pressure applied varying depending on type and thickness of the geomembrane and the speed of the machine varying depending on the ambient temperature [21]. With a base cost of HDPE - \$1.50/m², PVC - \$2.00/m², there are a number of geomembrane manufacturers in Australia including Jaylon, Industrial Plastics, Fabtech, Merit Lining Systems, atarfil, PMP Group and Geomembrane Australia.

9.2.5 Case Studies

One case study is the Bombay Presidency Golf Course in Chembur, Mumbai, the course was built on gravel and sand to provide for good drainage and lakes were constructed as obstacles [22]. However water was seeping out from the lakes into the gravel and sand, a decision was made in order to stop the seepage, to use 1mm thick HDPE geomembrane [22]. The water was removed from the lakes and 30 cm of mud was excavated using a Poklane [22]. The lake beds were aligned to obtain the desired evenness and contours, and Fibertex F-40 PP Nonwoven needle punched Geotextile was placed on the soil to protect the geomembrane from potential punchering [22]. The geomembrane was laid over the geotextile, and both were anchored in a 60 cm by 60 cm trench approximately 1 m from the edge of the slope [22]. A 30 cm layer of stoneless soil was placed over the geomembrane at the bottom of the lakes, and a 30 cm layer of fertile soil to support vegetation was placed on the side slopes [22]. A FC-700 Coir Geotextile, anchored with bamboo stakes, was placed on the side slopes to help establish vegetation and prevent erosion [22]. The lakes were then refilled and grass sapling planted on the side slopes [22]. When the monsoon hit Mumbai, vegetation grew fast and seepage was prevented [22].

Figure 9.2: HDPE Geomembrane [23]

Figure 9.3: PVC Geomembrane [24]

9.3 Geosynthetic Clay Liner

9.3.1 Function

Geosynthetic Clay Liners (GCLs) are often utilized in the sectors of mining, waste, and water management industries. However, their relevancy to pavements are evident through the product **Bentofix**. The organizations **Global Synthetics & Naue** has denoted their capability to employ GCLs within the production and construction of roadways within previous projects.

Their project within Wasser Bei Freiburg, Germany denoted the utilization of **Bentofix BFG 5000 Secutex R504** for the purpose of water reinforcement in a four-lane roadway. The liner consists of two needle punched geotextile layers that encase a layer of sodium bentonite allowing them to be most suitable for sealing applications.

9.3.2 Application

The application of utilizing the Bentofix GCL material within roadways and pavements are suitable as they are not only resistant to seeping, leakage, and natural elements but also highly effective in transmitting shear strength. The GCL design allows it to be thermally heated and subsequently its component fibers locked into place for long-term, high shear strength applications.

For the purposes of pavements within solar farms, the flat or very shallow environment and slope allows the **Bentofix X2 BFG 5300** and Bentofix **X5F BFG 5300** to be most suitable.

Figure 9.4: GCLs in Flat Ground Application

For the application of alternative less conservative design measures and optimizations to pavements within a solar array, the utilization of GCL would not fit its typical application. Furthermore, some of the synthetic's specifications such as its design to operate best and fulfill its sealing capabilities on slopes would be unfit for solar array environments and pavement designs of flat ground. Furthermore, with some of the previous projects carried out utilizing GCLs within roadways, a surface course layer is often still imposed.

In summary, GCLs are applicable for implementation in pavement design however, the market demonstrates other geosynthetic products would be more favorable, posing greater benefits and proven concentrated application.

Mechanical Properties

Table 9.1: Mechanical Properties of Material – GCLs (Pavement)

Tensile Strength (kN/m)	Roll Length (m x m)	Mass (kg/m^2)	Thickness (mm)	Internal Shear Strength (kPa)	Fluid Loss (mL)	Puncture Resistance (N)
14	4.85 x 40	5.55	6	35	18	2500

List of Complementing Products

Aside from the researched Bentofix product specified there are a range of similar products on the market that have a potential to also be suitable for employment within pavement design, however, these products have not proved to be utilized in a similar application or for the environment of solar arrays. The following products can be further investigated for the purpose of employment in pavement design:

- Bentosure
- Bentoliner
- Elcoseal

9.3.3 Sustainability Aspect

Maintenance	Life Cycle	Carbon Emission in Production	Cost (AUD)
- Waterproof - Desiccation - Root Protection - Barrier against Critical Liquids - Gas & Vapor Seals - Long Term Shear Strength - Direct coverage with Concrete & Lime Feasible - Damages can either be patched or else in larger scale cases completely new GCL is required. - Adhesives or bentonite paste, and material required for repairs.	- Life Span: likely over 100 yrs.	34% reduction approximately in comparison to conventional compacted clay liner. - Lower transportation carbon footprint. - 3.2 truckloads of clay for 2.5 acres (one-hectare)	- Per Roll: - Installation: 0.05 to 0.10 per m^2.

Figure 9.5: Sustainability Aspects – GCLs (Pavement)

9.3.4 Installation/Maintenance

The installation process overall in comparison to conventional clay liners is rapid and simple. A more specific installation process of GCLs within pavement, pathway and roadway development includes multiple stages.

1. Delivery & Storage
   - Within this phase, products must be kept dry and stored in a manner that allows them not to roll or slide.
   - Each roll can weigh in the range of 700-1500kg.
   - Transportation of roll should be accomplished via truck.

2. Subgrade Preparation
    - Subgrade preparation can be project specific however, many typical installation measures are required to be followed.
    - Subgrade Properties:
        - Gravel like material is not suitable for the installation of Bentofix products.
        - 80% of the soil must be finer than 0.25mm.
        - Smooth surface that is vegetation, rock, stick and stone free
        - Remove abrupt grade changes.
        - No protrusions extending 12mm.
3. Installation
    - Panels layout is to be determined prior to installation.
    - Bulldozer type heavy vehicle is required for unrolling product.
    - Must be straight in layout.
        - Any bends or corners require a cut.
    - Lie flat over surface.
4. Anchorage
    - Anchorage points may rely on a slight slope to the landscape – dug out trench layout for anchoring the liner.
5. Seaming
    - Geomembrane-based GCLs can be welded together.
    - Edge clearance required (estimated 150 to 230mm).
    - Minimum overlap of 500mm.
    - Material cannot be left uncovered for an extended duration of time during construction.
6. Sealing around Penetrations & Structures
    - Easy and readily available conventional tools for cutting.
    - Can be sealed around piping or structures embedded in subgrade.

7. Cover Placement

    - Cover soils required are to be relatively fine (ranges from fine to 25mm).
    - Soil cover requires construction equipment to minimize stress.
    - No direct contact between GCL material and vehicles.

Manufacturers

Naue
This organisation is a manufacturer of geosynthetic materials, based in Germany with offices in Malaysia, Poland, France, Romania, Netherlands, the UK, and the USA. They are manufacturers of Bentofix and Bentofix X GCLs. Their product development and design enables a reduction in CO2 via the lower transportation requirements in comparison to conventional clay liner products. Naue denotes experience with the utilization of the Bentofix product in the realm of pavement and road designs.

Geoline
This organisation is a manufacturer, supplier, and installer for Elcoseal GCL products. Furthermore, they offer Geomembrane, Geotextile and Geoweb products and/or solutions. Global Synthetics This organisation is the primary distributor and manufacturer of Bentofix GCLs with Australia. They, supply products such as Bentofix bi-axial geogrids for sub-base reinforcement, uni-axial geogrid for slope reinforcement and other geotextiles, non-woven geotextiles and geonets.

Cirtex
This organisation is the primary focused on delivering solutions and specifics to installing products such as Bentosure GCL.

9.4 Geocomposites

9.4.1 Function

Geocomposites are defined as hybrid materials prefabricated by combining different types of geosynthetic products with other materials, which are able to achieve drainage and reinforcement functions simultaneously while minimising the constraints of conventional materials [25]. The Geocomposites have multi-functions involving:

- **Stabilisation:** Due to the interlock and lateral confinement of the granular fill, geogrid is mechanically stabilised and capable of limiting differential settlement, reducing road fill depths and increasing the bearing capacity.
- **Separation:** Separating and preventing two distinct soil layers or different materials from intermixing while maintaining the performance of individual components.

- **Filtration:** While restricting the migration of fine soil particles, the retained soil remains permeable.

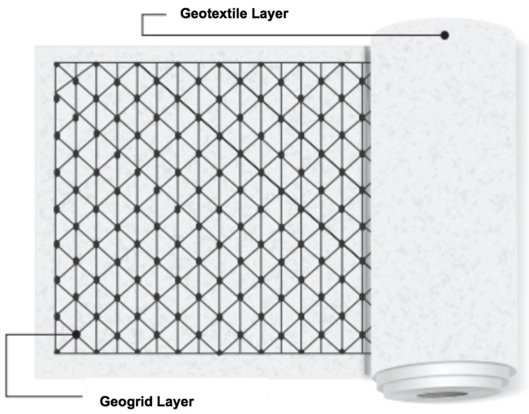


Figure 9.6: LamGrid® Green Geocomposites from Geofabrics

9.4.2 Application

Commonly applied in rail and road applications with soft subgrade soil conditions and high water levels such as composite pavements, airport runways, road maintenance and repair. Offering multiple functions such as stabilisation, drainage, filtration, separation and reinforcement [26]. Geocomposites contribute to improving structural performance, reducing construction time, improving the durability and achieving environmentally friendly.

Manufactures: Geofabrics, Cirtex, Global Synthetics

9.4.3 Sustainability Aspect

The raw materials of Geocomposites products differ from different manufactures, most of them are made from recycled plastic materials. For example, LamGrid Green from Geofabrics is made from Australian recycled plastic geotextile layer bonded with a polypropylene (PP) geogrid layer. PP is regarded as one of the most sustainable materials due to its excellent physical properties and adaptability [27]. PP is more environmentally friendly than some other plastic materials. It's recyclable and doesn't release as may toxins as plastic such as PVC. It also breaks down more quickly, taking just 20-30 years compared to over 500 years for some other plastics.

9.4.4 Installation/Maintenance

Benefits:

- There is a 30% reduction in aggregate layer thickness when compared with the original stabilised layer.

- Save installation time by combining the geotextile and geogrid layers during fabrication procedures instead of installing two conventional layers separately.

- Minimising the required cost, time and labour by reducing the need for transportation and excavation of subgrade soils. With mechanically stabilised layer, the lifespan can be increased by 3 times and the long-term maintenance costs can be reduced by up to 50%.

Restrictions:

- **Storage:** The geocomposite products should be protected from the moist environment and placed on a dry, flat surface. Ultraviolet Radiation (UV) protection is required. Rolls should not exceed 3 high.
- **Surface preparation:** The surface should be smooth, dry and free of loose stones in order to avoid any voids between the geocomposite products and underlying layers. It may be installed on uniformly textured surfaces with less than 5mm of macro-texture.
- **Installation/Placement:** Wrinkles and folds should be avoided during the installation process and the geogrid component should be installed facing up. The product can be cut, sprayed with additional binder materials and overlapped when wrinkle exists.

9.4.5 Case Studies

- **Project:** New Tasmanian road stabilising
- **Product:** LamGrid® Green Geocomposite
- **Manufacture:** Geofabrics
- **Project Description and Problem:** A new road was planned to be constructed on the site where buried pipes were located at a shallow depth. The excavation depth was restricted as a result. Due to the nearby construction requirement, it was anticipated that the road would be stabilised to carry heavy vehicles with axle loads of up to 12 tonnes. The asset owner contacted Geofabrics to provide a solution that would limit the loading on the pipes to the permitted level [28].
- **Solution:** It was recommended to incorporate LamGrid Green into the pavement, which is a geocomposite product combining Bidim Green geotextiles and Tensar Triax geogrids. Additional product application assessment was required to determine if the product could be applied without thickening the pavement. Initially, it was assumed that Finite Element Analysis (FEA) would be required to arrive at a solution based on the information provided. Nevertheless, by adopting the T-value method for working platforms developed by Tensar, the Geofabrics technical team was able to provide the client with a preliminary evaluation without resorting to FEA. The result showed the geocomposite product provides good interlocking properties and enough protection of the subgrade materials. Thus, client could avoid using conventional materials such as steel and concrete to increase the thickness of the pavement. The entire project costs and duration were significantly saved by using the LamGrid grocomposite product that Geofabrics proposed [28].

9.5 Geotextiles

A geotextile is a permeable and flexible material fabric that consists of thermoplastic polymers, such as polypropylene (PP) or polyester [29]. Geotextile fabrics are used to improve soil characteristics, which designed to perform one or more functions such as separation, filtration, reinforcement, drainage, protection and stabilisation when used in conjunction with soils [30]. There are two types of geotextile fabrics, non-woven and woven. Non-woven geotextiles are fibre sheets that have a three-dimensional (3D) fibre structure, which provides a high porosity, variation in pore size, and water permeability, and thus have been applied in filtration, separation, and drainage applications. Woven geotextile fabrics, on the other hand, exhibit superior mechanical properties, which are mechanically stronger than non-woven geotextiles [31]. The following sections introduced and described different aspects of two commercially available non-woven and woven geotextile products, namely Bidim® Green Non-woven and TenCate Mirafi-RSi, respectively.

9.5.1 Bidim® Green Non-woven

Bidim® Green is a premium non-woven geotextile fabric, illustrated in Figures 9.7 and 9.6, made from a combination of Australian recycled polyethylene terephthalate (PET) polymers and virgin plastic material. This non-woven geotextile is designed to provide an effective and economical solution to a multitude of engineering applications [32]. Not only this product offers functions that are applied in roads applications but also provide other functions such as drainage and protection which can be applied in applications such as embankments and liner protection.

Figure 9.7: Bidim® Green Non-woven Fabric [32]

Functions:

1. **Separation:** Bidim®Green non-woven geotextiles can be used in the construction of roads, railways and embankments where the ground is soft and unstable. By using a layer of geotextile, it is to separate the soft ground from the fill material, which reduces the amount of fill required, increase the life span of the road or rail structure and cut long-term maintenance costs.

2. **Filtration:** As Bidim®Green non-woven geotextiles are highly porous, they allow water to pass through while preventing soil migration. According to the manufacturer, the manufacturer of this product, Bidim® Green geotextiles are deemed to be more cost-effective than natural filters, when used in revetment and subsoil drainage projects.

3. **Drainage:**With a three-dimensional structure, Bidim®Green non-woven designed to improve drainage performance, which is ideal for use in subsoil drainage systems. The geotextile will assist in the removal of water from road and railway works, sports fields and behind retaining walls [32].

Applications:

1. **Roads:** Separation and filtration under the road formation is critical in road construction. Water ingress on road pavements poses the most significant damage potential to any road, thus rapid removal of this water is of the utmost importance. As Bidim® being the only bi-dimensional geotextile available on the market, meaning it has the same strength properties in both directions, it allows the water to pass through while preventing soil from migrating [32]. Generally, a standard road construction practice requires the inclusion of road edge drainage systems. In order to optimise the performance of these drains, a geotextile with high flow rates is desirable. With 3D structure design, Bidim® provides numerous flow paths that allow water to flow at rates in which exceed most natural materials it is placed in contact with [32].

2. **Embankments:** Soft ground or poor quality ground poses a significant contamination to the fill material when they come in contact with each other, leading to a reduction in performance of the fill material. Geotextiles often use to separate the two distinct elements by limiting fill material from being contaminated and preventing subsequent strength loss [32]. Construction in this environment can place the geotextile separator under high stress with forces from rock placement and equipment loads needing to be transferred into the poor quality material. Bidim® Green non-woven geotextiles are ideal for this application as it combines high elongation with high strength to provide unsurpassed toughness and survivability characteristics [32].

Sustainability Aspects

Bidim® Green non-woven geotextiles made from Australian recycled PET polymers, wrap and core. According to its manufacturer, Production currently uses between 500 - 1,000 tonnes of Australian sourced recycled materials every year [32].

Installation/Maintenance

Bidim® Green geotextiles are supplied fully wrapped in rolls up to 6m in width to minimise wastage and laps. However, rolls lengths varies depending on the grade of the product, which requires different storage spaces. Figure 9.8 below shows the dimensions of Bidim® Green range.

BIDIM GREEN RANGE

Bidim Green A Grade	Strength Class	Widths	Length
A14G	A	2m, 3m, 4m, 6m	250m
A19G	B		200m
A24G	-		200m
A29G	C		150m
A34G	-		150m
A39G	D		125m
A44G	-		125m
A49G	E		75m
A64G	-		75m

Figure 9.8: Dimensions of Bidim®Green Nonwoven Geotextile Range [32]

Manufacturers

Geofabrics, Cirtex, Global Synthetics

Case Studies:

- **Product Name:** Bidim® Green Nonwoven Geotextile
- **Project Description:** The Bruce Highway was earmarked to be upgraded to 6-lanes between Caloundra Road and the Sunshine Motorway, including major upgrades to both interchanges and a new 2-way service road for local traffic. Australia's first ever diverging diamond interchange has been included in this design, offering improved traffic flow, while minimizing the project footprint through this sensitive ecological region. The upgrade separates long distance traffic from local traffic, allowing the highway to function as a high-speed, high-volume corridor. Not only will flood immunity of this highway section be improved but the project will support the growth of the Sunshine Coast region well into the future.
- **Solution:** Bidim Green was used in a combination with Megaflo Green as the key products for this project. However, other Geosynthetic products including Geogrids, TenCate Mirafi® RSI and PET and were used to assist the success of this project [32].

9.5.2 TenCate Mirafi®RSi

Having similar functions to BidimBidim®, TenCate Mirafi®RSi are the first multi-functional woven geotextiles designed to improve reinforcement, separation, drainage and filtration and material interaction between the aggregate layers [33]. The outcome is an assured significant improvement in road or subgrade performance with the added benefit of reduced sub-base material volumes when constructing over soft soils.

Functions:

- **Separation:** TenCate Mirafi®RSi has a unique double layer construction with uniform openings which provide consistent filtration and flow characteristics of a fine to coarse sand layer [33]. It is also proven to provide effective prevention of aggregate mixing and loss of sub-base material into soft subgrade [33].

- **Reinforcement:** TenCate Mirafi®RSi has a high transverse tensile modulus, meaning it provides efficient absorption and distribution of tensile load. In addition to this, it also has a high interaction coefficient which provides superior load transfer between fill and reinforcement [33].

  - **Durability:** Have robust damage resistance for moderate to severe stress installations [34].

  - **Mechanical Properties:** Have initial tensile stiffness modulus (typically at 2% strain), which is a key performance property for the reinforcement function and effectiveness, at the same time provides excellent separation to prevent contamination of the base materials [34].

  Figure 9.9 shows mechanical properties such as tensile strengths, CBR puncture strengths of the TenCate Mirafi®RSi series, namely RS 380i and RS 580i.

- **Permeability:** Having high permeability, the woven geotexile allows efficient release of pore water pressure that usually develops in the sub-grade when wheel loads are induced, helping to minimise undrained conditions and reduce plastic deformations in the sub-grade [33]. Figure 9.9 shows hydraulic properties such as flow rate and permittivity of the TenCate Mirafi®RSi series, namely RS 380i and RS 580i.

PROPERTY	TEST METHOD	UNITS	RS 380i	RS 580i
MECHANICAL PROPERTIES				
Characteristic Tensile Strength at 2% Strain CD	ASTM D4595	kN/m	20	26
Characteristic Tensile Strength at 2% Strain MD	ASTM D4595	kN/m	8	9
CBR Puncture Strength	ASTM D6241	N	6,600	9,000
Grab Strength	ASTM D4632	N	1,500	2,100
Trapezoidal Tear Strength	ASTM D4533	N	600	700
G-Rating	Austroads	-	7,000[1]	10,000[1]
HYDRAULIC				
Flow Rate	ASTM D4491	$L/m^2/sec$	50.8	50.8
Permittivity	ASTM D4491	sec^{-1}	0.9	1.0
SOIL RETENTION				
Apparent Opening Size, O_{95}	ASTM D4751	mm	0.43	0.43
Effective Opening Size, O_{90}	ISO 12956	mm	0.35	0.30
SOIL INTERACTION				
Interaction Coefficient (Direct Shear)	ASTM D5321	-	0.80[1]	0.80[1]
Interaction Coefficient (Pull-out)	ASTM D6706	-	0.89[1]	0.90[1]
Resistance to Installation Damage	ASTM D5818	% strength retained	90[1]	90[1]
UV Resistance (at 500 hours)	ASTM D4355	% strength retained	90	90

Figure 9.9: Material Properties of TenCate Mirafi®RSi Series [34]

Applications

- **Roads and Highways:** Roads and highways today not only have to support increasing traffic volume, but also increased axle loads, requiring more sophisticated design to reduce construction costs. The use of engineered woven geotextiles to form a subgrade improvement layer in pavements over soft soils can save on costs by allowing for a reduction in subbase thickness and faster construction times [34].

- **Upaved and Haul Roads**: TenCate Mirafi® RSi Engineered Woven Geotextiles provide engineers with an alternative solution to traditional solutions for haul roads, unpaved roads and load supporting platforms, combining all the critical functions that contribute towards subgrade reinforcement [34].

Sustainability Aspects

As this material are not made with recycled materials as compared to Bidim®Green non-woven geotextiles, it is not known to be sustainable and manufacturer of this product is not able to provide further information on this.

Installation/Maintenance

It requires minimal manpower to install TenCate Mirafi®RSi woven geotextile, as it is easy to lay and align. It should be placed flat and tight with no folds or wrinkles. The rolls should be oriented as shown on plans to ensure the principle strength direction of the material is placed in the correct orientation [33, 34]. Prior to fill placement, it should be held in place using suitable means such as pins, sandbags, staples and soils to limit movement during fill placement [33, 34].

Manufacturers

Geofabrics and Global Synthetics.

Case Studies

- **Product Name:** TenCate Mirafi®RSi
- **Project Description:** Northland rail received a significant government investment totalling $94.8 million, KiwiRail were tasked with replacing five bridges and repairing thirteen tunnels in total. However, due to the soft soils in the area a haul road needed to be constructed to handle the stress of 2 x 100 tonne cranes driving over, while the bridges needed to be completed before the end of September, creating a tight deadline for the project. With every delay or day behind, KiwiRial would incur significant costs associated with the rail line being shut down [35].
- **Solution:** By using TenCate Mirafi® RSi, a number of benefits for the contractor and enduse client have been delivered. As local New Zealand business, all products were supplied in a timely manner, leading to the shorter lead times. Another benefit that this product offered is less materials/products required. Reducing the design from multi-layer to single layer halved the time required to install each section of the road. With a total area of 16,000 squared meter,the time saved across the project was significant [35].

9.6 Geofoam

9.6.1 Introduction

As the increasing demand of the new roads, sometimes the pavement is required to be constructed over the loose or soft soil that might not be able to support extra loads. In order to resolve this problem, designers need to find a new material and accelerate the construction schedules. In that case, EPS geofoam is used to replace the compressible solids or the heavy fill materials.

Not only because the high compressive resistance of geofoam ensures that it could adequately support traffic loading, but also because it could save the construction duration. Geofoam is the Lightweight material, which the density of it is approximately 1/100th of others (lightweight fill application, to prevent the associated issue of unacceptable rates of settlement). It has the Small Poisson's Ratio high self-sustaining by reducing the lateral pressure as backfill material such as retaining wall.

Figure 9.10: Geofoam

Advantage

The application of Geofoam could be cost-effective and time-effective during the construction stage. The reason to indicates that geofoam is time-effective is not only because this material is easy to be handled without the application of other special equipment, but also because this material is engineering product and has been tested in advance. There is no need to have undergone QA test like other fill materials. Additionally, the bad weather has no impact on the geofoam construction.

Sustainability

Geofoam has moderate impact on the environment.

On the one hand, this material is environment friendly. First of all, geofoam is not biodegraded, and it is chemical inert in the soil and water, so it will not contaminate the ground and the ground water. Secondly, this material could be recycled. In addition, during the manufacture of the geofoam or any other polymeric foam, none of the CFC or HCFC is used, which could be a major pollution for the environment. Finally, if EPS is burned by accident or on purpose, as being part of the waste-to-energy program, it still will not pollute the environment since the composite of geofoam is mainly carbon dioxide and water.

On the other hand, the application of the geofoam might cause zone depletion due to the usage of the low thermal conductivity blowing gases such as chlorofluorocarbon 11 and 12 (CFC-11 and

CFC-12). Additionally, sewers and waterways could be obstructed by the small parts including raw beads, prepuffs etc., which has already been found in the digestive tracts of fish (Huntsman, 1999a).

9.6.2 Installation

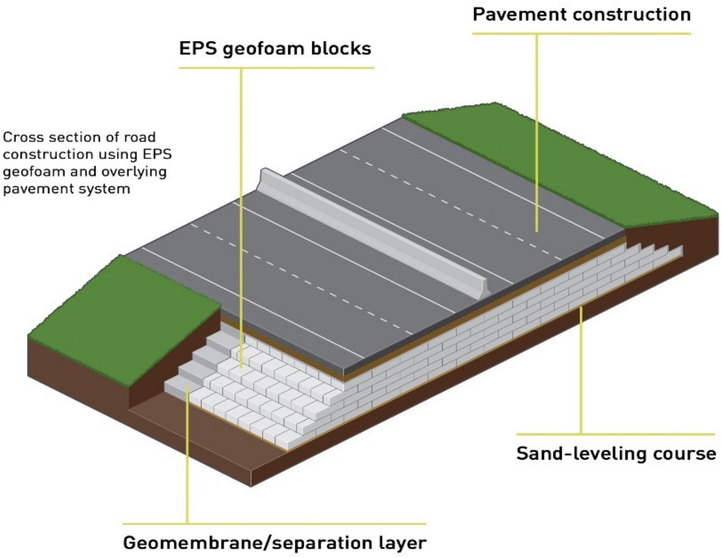


Figure 9.11: Installation of Geofoam

A typical pavement construction steps of using the geofoam from bottom to top are listed below:

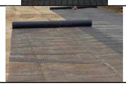
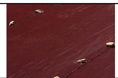
1. A layer of sand is compacted above the subgrade exaction to provide a flat construction surface with free draining.

2. Put the EPS geofoam to the height required and ensure that the geofoam blocks stagger the vertical joints during each step, or a continuous vertical seam might occur.

3. If needed, a separation layer could be set between the geofoam and pavement system. This layer has two functions. One is to improve the overall performance of the system and life span by reinforcing, separating and/or filtrating; Another is to improve the durability of the geofoam during and after the construction. The materials of this layer could be geotextile, geomembranes, etc. based on the requirement.

4. The layer above the separation layer is the pavement system, which typically consisted of selected fillers, subgrade gravel and asphalt/concrete driving surface [36].

10 Evaluation Table for Pavement Optimisation

Criteria				Ease of Installation	Product Costs	Effectiveness	Environmental Impact	Maintanence
ID	*Material Type*	*Options*	*Images*					
1	Asphalt	-		High - specialised vehicles & machinery	$65-150/m2 - differ by factors	Tensile Strength: 120kN to 1290kN per m2 - range of average mixtures	High	Moderate
2	Geosynthetic Clay Liner (GCL)	Bentofix X2 BFG 5300		Modertate - some heavy vehicles required	$0.05-0.10/m2	Tensile Strength: 14kN - Low Top Soil can Damage Material, Unconventional Application	Low	Moderate
		Bentofix X5F BFG 5300		Moderate - some heavy vehicles required	$0.05-0.10/m2	Tensile Strength: 14kN - Low Top Soil can Damage Material, Unconventional Application	Low	Moderate
3	Geogrids	DuraGridX		Simple roll out application; Can be installed manually or by machine	$3-5.5/m2 (from citrix) $6.02/m2 (from NZ manufacturer)	UTS 20-40kN Tensile Strength at 2% Strain: 7-14kN Achieved ISO9001 certification and has passed the CE certification	Low	Life span over 100 years
		TENAX® 3D Grid T		Smooth ground, unroll geogrid, and apply fill materials (procedure depends on the subgrade shear strength)	$7.7-8/m2	550kN Modulus Radial Stiffness at 0.5% Strain is 321 kN/m - Suitable for Small-Medium Aggregates	Low	Life span over 100 years
		mastaGRID® Poly Geogrid 40		Simple roll out application	$4.41/m2	UTS 40kN Tensile strength at 2% strain 17.5kN Achieved ISO9001 certification and has passed the CE certification	Low	Designed to reduce long-term creep
4	Geomembranes	HDPE		Ground falterned, projections removed, 1.5% slope required if pressure bulidup possible, trench anchoring required	$1.50/m2	15000 kN/m2 at 2% strain	Contains some Petrochemicals	Low
		PVC			$2.00/m2	5000 kN/m2 at 2% strain	Low	Moderate
5	Geocomposites	LAMGRID® Green Non-woven (from Geofabrics)		Faster installation available by combining bidim Green and Tensar Geogrids Geocomposites	A14: $4.54/m2, A19: $4.71 /m2, A29: $5.07	Ultimate tensile strength: 8kN/m to 37.5 kN/m, dependiing on grading	Material: Recycled Plastic Material	Increased service life by 3 times, reducing long-term maintenance costs
		ProGrid® GC/GB Compo (from GlobalSynthetics)		Surface should be as smooth as possible, dry, and clean with cracks and potholes. Wrinkles and folds should be avoided	-	GC: - Ultimate tensile strength ≥ 50kN/, - at 2% elongation ≥ 9 kN/m, GB: - Ultimate tensile strength ≥ 50kN/m, at 2% elongation ≥ 40 kN/m	Material: Polyester(PET) or Glass Fibre Geogrid + PET Geotextile, bonded with Asphalt layers	Extend service life for pavement layers
		GRIDTEX (from Cirtex Australia)		Save construction time as it can be laid in a single operation instead of laying grid and textile separately	-	Geogrid component: 10.5 - 14kN/m at 2% strain, 30 - 40 kN/m ultimate tensile strength. xtile component: 14kN/m ultimate tensile strength. Wide rolls for efficiency.	Material: Polypropylene (PP) - Eco-Friendly Material	Durable and High Resistance to Damage
6	Geotextiles	Bidim-Green Non-Woven		Fully wrapped in rolls up to 6m in width to minimise wastage and laps. Installation can be assisted using contractor supplied spreader bar	$1.46/m2	Wide Strip Tensile Strength: 8 - 37.5kN/m. Grab Tensile Strength: 500-2620N. CBR Burst Strength: 1500-6400N	Made with a combination of Australian recycled PET and virgin plastic material. Reduce energy use and carbon emissions by replacing or reducing the use of products such as soil & aggregate materials. Lower carbon emissions by reducing the volume required for quarry materials and heavy transport to construct road and rail platforms	Design life of over 35 years.
		TenCate- Mirafi RSI		Easy to lay and align. Prior to fill placement, should be held in place using sutiable means such as pins, sandbags, staples and soils to limit movement during fill placement	$4 - $4.40/m2	For Mirafi RS-380i Tensile Strength: 1500N, CBR Puncture Strength: 6600N. For RS-580i Tensile Strength: 2100N, CBR Puncture Strength: 9000N	Moderate	-
7	Geofoam	-		-	$80/m2	-	Moderate - recycled, soil friendly, but release gases	-

11 Proposed Solution(s) For Pavement

DuraGrid passes all criteria in the evaluation table.

11.1 Geogrid

11.1.1 Benefits

The geogrid has the following cost saving by optimising its usage to reduce thickness of the sub-base layer in a pavement section. Figure 2.4 compared different pavement sections and Figure 11.2 shows the cost comparison between geogrid, geotextile per meter squared, as well as the total product savings.

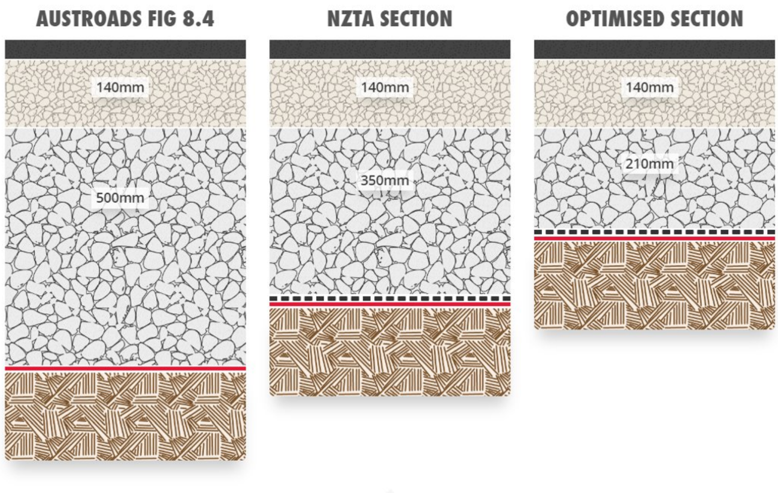


Figure 11.1: Comparison of different pavement sections

PAVEMENT THICKNESS	640mm	490mm	350mm
GEOGRID	N/A	Tenax 3D HT View Product	Tenax 3D HT View Product
GEOTEXTILE	DuraForce® AS410 NZTA F/7 Strength Class C View Product	DuraForce® AS280 NZTA F/7 Strength Class B View Product	DuraForce® AS280 NZTA F/7 Strength Class B View Product
SAVINGS PER METRES SQUARED	$0.00	$9.25	$21.15
TOTAL PROJECT SAVINGS	$0.00	$41,625	$95,175

Figure 11.2: Cost comparison between geogrid and geotextile per meter squared

Cost

The estimated cost is about \$3-5.5/m².

Sustainability

The geogrid embedded into ground does not require maintenance. It is estimated to have over 100 years life span when not exposed to UV.

11.1.2 Applications

Duragrid has been applied to Queenstown International Airport for runway widening. The application of Duragrid was to reinforce the new runway pavement. A layer of DuraGrid was placed directly over the DuraFlow drainage composite to give reinforcement to the pavement [15].

11.2 Geotextile

Both of the non-woven and woven geotextiles, namely Bidim® Green Non-woven and TenCate Mirafi®, passed most of the criteria, where product costs and environmental impact being the highest prioritised criteria in products evaluation.

11.2.1 Benefits

1. **Bidim® Green Non-woven**

   - **Cost-effectiveness:** It is the cheapest geosynthetic product compared to other solutions with a price range from \$0.80/m^2 - \$2.47/m^2 for different classification. The average price is \$1.46/m^2. Table 11.2 listed price range based on their class. Apart from having the cheapest product cost, its packaging also helps in reducing transportation cost. This is because it comes with Wider and longer rolls up to 6m to reduce waste with overlaps and savings on transportation costs.

     Table 11.1: Price Quotation for Bidim Green Nonwoven Geotextile range

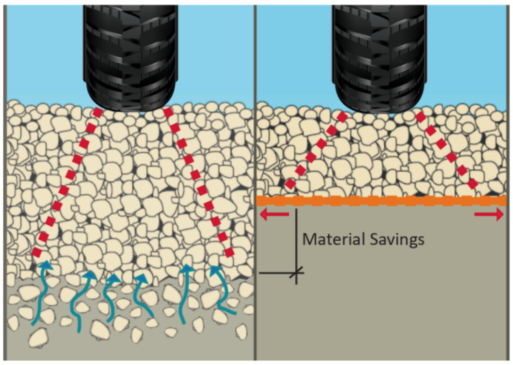
Bidim Green Nonwoven Geotextile Classification	Price/m^2
Bidim Green A14 (Class A) R63	\$0.81/m^2
Bidim Green A19 (Class B) R63	\$0.99/m^2
Bidim Green A29 (Class C) R63	\$1.27/m^2
Bidim Green A39 (Class D) R63	\$1.76/m^2
Bidim Green A49 (Class E) R63	\$2.47/m^2

   - **Sustainability:** Another benefit of this genotextile is being sustainable. It is made from Australian recycled PET polymers, wrap and core. The production currently uses between 500 - 1,000 tonnes of Australian sourced recycled materials every year. By utilizing the nonwoven geotextile, the environment can be protected in a number of ways, such as reducing energy use and carbon emissions by replacing or reducing the use of products such as soil aggregate materials, and lower carbon emission by reducing the volume required for quarry materials and heavy transport to construct road and rail platforms.

- **Life-span:** It was claimed to have a design life of over 35 years, which could be a semi-permanent solution to road pavements application.

2. **TenCate Mirafi® RSI:** This woven geotextile product was chosen based on two criteria, mainly on the cost-effectiveness and effectiveness/performance.

   - **Cost-Savings:** the geotextile can help deliver material cost savings of up to 33% by reducing the amount of base material required, which is a significant cost reduction. Example of temporary access track showing use of site-won aggregate. Savings of up to 33% include reduction in pavement thickness, as well as lower costs to import fill, casting to spoil and costs to remove large, site-won materials as in Figure 11.3 below.



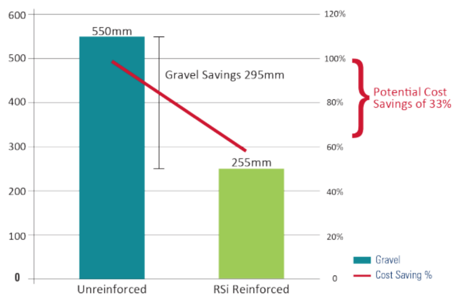


Figure 11.3: Saving on site-won aggregate (left). A comparison of Pavement thickness required between Unreinforced and TenCate Mirafi RSI Reinforced (right) [34].

   - **Techanical Performance:** Superior reinforcement strength and soil interaction integrated with high water flow and soil retention capabilities.

     - **Robustness**: Having extreme robustness that Withstands the effects of rough dumping and filling with minimal damage.Performs extremely well with large site-won fill. It also has a robust damage resistance for moderate to severe stress installations.

     - **High Transverse Tensile Modulus:** Efficient absorption and distribution of tensile load, with an initial tensile stiffness modulus (typically at 2% strain); a key performance property for the reinforcement function and effectiveness, and at the same time provides excellent separation to prevent contamination of the base materials.

     - **High Interaction Coefficient:**
       Superior load transfer between fill and reinforcement.

  - **High Permeability:** Efficient release of pore water pressure which is suitable for installation over very soft wet soils.

- **Sustainability:** Extremely easy to lay and align which requires minimal manpower.

11.2.2 Limitation

1. **Bidim® Green Non-woven:** requires a spreader bar to be assisted in handling and installation.

2. **TenCate Mirafi® RSI:** the price is higher than Bidim® Green Non-woven and other solutions such as geomembrane and geo clay liner. Table below listed price quotation for two different grades.

Table 11.2: Price Quotation for TenCate Mirafi® RSI Range

Bidim Green Nonwoven Geotextile Grades	Price/m²
Mirafi RS380i – CBR Above 1-1.5	$4.00/m²
Mirafi RS580I – CBR Below 1-1.5	$4.40/m²

11.2.3 Manufacturer(s)

Geofabrics Australia Co Ltd

12 Scouring Control Background

12.1 Solar Farms Relevancy

The major issue from the stormwater that is caused by the solar arrays is the centralized discharge of rainfall runoff at the solar panel drip line. The surface of the solar panels are flat, which could channelize and accelerate the flow like the un-guttered roof. The channelised runoff will be landed from the surface, which will have major impacts on the grass, causing soil scouring, soil erosion and pollution. It is significant to create stormwater management system and it is also important to keep the system away from being drowned by the runoff flow or sediment accumulation.

If the soils under the solar panel edge are not stabilized properly, the scouring and soil erosion will happen because of the concentrated flow at the drip edges. Under this circumstance, the sediment will be transported to other areas, reducing the capacity of infiltration, which will cause flooding in the certain area [37].

12.2 Conventional Solutions

Scouring within the context of solar farms is the erosion of sediments, within cut or dug drainage waterways, due to fast-moving water. Therefore, scouring can heavily impact the structures and natural landscape of solar farms if not properly protected against. Geosynthetics are a solution that has been heavily investigated over the project duration; they are man-made materials designed to improve soil conditions.

Within this aspect of this project not only has geosynthetic materials been investigated however, alternative approaches such as bio meshes, mats and some conventional approaches to generate a comparative and comprehensive analysis.

Within this section of the project investigation upon the stormwater drainage system scouring protection measures, the conventional solutions have been compared within the section *14 - Evaluation Table for Scouring Optimisation*. These conventional solutions have information sourced from a previous investigation and documentation supplied by RBG under the project named *19612-RBG-ZZ-XX-CO-CV-SW002-WSF-Channel Protection Options*. The evaluation table supplied in this document accommodates the information and details of the conventional solutions under the first column *ID 10 & 16*. These items known as **Rock Lined Channels** and **Concrete Canvas** are the favourable and typically utilised by clients in solar farms or general applications in stormwater and drainage systems for protection against scouring. These typical solutions on the market are typically favourable choices however, are relatively higher cost compared to our investigation and findings. The sustainability scope is also limited within these approaches due to extensive transportation demands, production process, material requirements, installation and machinery requirements.

12.2.1 Introduction

For areas where scouring of channels would occur, rock protection is standard to prevent soil erosion due to concentrated runoff. A soil base that erodes can cause panel hardware to shift and negatively impact panel efficacy. Rock can be used as a surface lining within stormwater drainage channels for a variety of reasons, including scour protection, aesthetics (often incorporating round river gravels) and as a stable surface that can eventually incorporate vegetation.

Figure 12.1: Rock Lined Channels for Scouring Protection [38]

12.2.2 Pros and Cons

Benefits

- Rock lined channel protection method is common and efficient to construct.
- Simple to install and maintain.
- Rock protection is better suited for more flexible protection because it adapts to the shape and natural distortion of the soil.
- Easy to incorporate for decreasing water velocity and protecting slopes and/or soil from erosion.
- Rock protection also provides some water quality benefits by increasing roughness and decreasing velocity of flow and inducing settling.
- The labor and expenses associated with removing or relocating rocks are costly.
- Aesthetic appeal benefits [39].

Disadvantages

- It is subject to site, locality, contractor and supply variables.
- Concrete blocks and rocks are cumbersome for transportation.
- Potential risks of hitting and damaging the solar panels during the installation process.
- Concrete and rocks are quite expensive when material, transportation and placement costs are considered.
- Concrete doesn't allow for as much vegetation. Vegetation helps enhance solar farm performance because during drier months, when erosion might be less of a concern, dirt that gathers on rocks and concrete can generate dust that harms panel performance.
- Rocks don't absorb any water, it doesn't entirely stop a flood from occurring.

12.2.3 Feasibility (Installation)

Requirements

- Rock size is primarily dependent on the flow velocity (V), rock shape (round or angular), and rock density (Sr) [40].
- In most situations the nominal (d50) rock size is between 100 mm to 450 mm. For rock sizes greater than 450 mm, the placement of two layers of rock may become impractical, thus alternative channel linings are generally considered [40].
- If the rock is placed on a dispersive (sodic) soil, then prior to placing the filter cloth, the exposed soil must first be covered with a layer of non-dispersive soil or geotextile products [40].

Common Construction Problem

- Reduced channel flow capacity
  - Inappropriate placement of the rock, either due to inadequate design detailing, or poorly supervised construction practices.
  - Inadequate channel excavation and excess rock fill has reduced the flow capacity under the footpath bridge causing flows to regularly spill from the drain.
- Rocks placed above the adjacent ground level
  - Once placed, the top of the rock-lined surface should allow the free entry of water into the drain.
- Restricted flow entry into a drain

  - Drainage channels need to be 'over-excavated' such that, once the rock-lining has been placed, the final channel invert levels and dimensions match those presented within the design drawing.

- Insufficient cross-sectional depth
  - Water flow is expected to spill out of the channel and pass along the outer edges of the rocks causing erosion.

Level of Scouring Protection

- Acceptable: Rock lined channels are sufficient for erosion control in solar farms with appropriate designed rock sizes and grades to satisfy the energy requirement and resistance to run-off velocities.

12.2.4 Costs

From RBG technical memorandum 'Creek Diversion Channels – Alternate Scour Protection Options' [38]:

- Rock including installation: $61.75 per m^3.
- Geofabric products: $2-$4 per m^3 (Rock must be placed over a layer of suitably graded filter rock or geotextile filter unless all voids are filled with soils).

12.2.5 Mechanical Properties

Sufficient for scouring protection within solar farms with rock sizes designed to suit the energy requirement and critical flow velocity.

12.2.6 Sustainability Aspects

Environmental Impacts

- Affecting the habitat of aquatic life: Rip rap stones reflect sunlight into the water, which can raise the water temperature to an unsafe degree for the fish and other organisms living there.
- High demand for rock transportation results in significant emissions of greenhouse gases.
- The production process of concrete requires the consumption of fuel such as coal, which also increases carbon emissions and is not conducive to environmental protection.

Maintenance

- Affecting the habitat of aquatic life: Rip rap stones reflect sunlight into the water, which can raise the water temperature to an unsafe degree for the fish and other organisms living there.

- High demand for rock transportation results in significant emissions of greenhouse gases.
- The production process of concrete requires the consumption of fuel such as coal, which also increases carbon emissions and is not conducive to environmental protection.

- Regular inspection and maintenance are required: Rock protection should be checked at least annually and after every significant storm event [41]. If the riprap has been damaged, it should be repaired immediately before further damage can take place. The outer edge of rock protection should also be checked periodically to ensure water flow into the drainage system will not cause erosion issues along the edge.
- Concrete riprap is susceptible to undermining, moving and cracking, as well as erosion at the perimeters. This damage is often difficult to detect and can be challenging to repair.

13 Alternative Solutions for Scouring Protection

13.1 Reinforced Turf Mat

Enkamat is a dense three-dimensional permanent turf mat with an open structure as seen in Figure 13.1, made from high quality poly-amide PA mono-filaments which are welded where they cross. The mat is used when naturally grown vegetation cannot prevent soil erosion on its own [42]. Enkamat can be used in many areas when erosion takes place, such as embankments, slopes and spillways, river banks, canals, landfills, ditches, channels and reservoirs. The mat is light, flexible and does not float in water, low flammability and has high resistance to weathering and UV radiation [42].

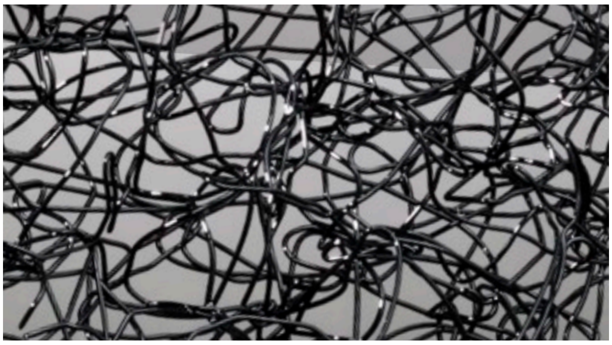


Figure 13.1: Three-Dimensional Open Structure of Enkamat

13.1.1 Function

Enkamat functions as a protective reinforcing and intermediate layer between natural vegetation and soil. It provides protection above and below the waterline, resulting in a permanent solution. Either seeded, filled with topsoil or mulched, the mat keeps the fertile soil in place and prevents the fill from being washed out. Vegetation soon establishes itself with root systems that are reinforced by the mat's structure. Enkamat creates an artificial root structure by its high filament density – up to 2980m filaments per squared meter. The tough filament core structure which has more than 95% open voids is unique to the mat as this allows soil to be contained within the mat effectively preventing it from being eroded away by rain or wind. The structure also slows down wind speed and percolating water, thus preventing erosion and even promoting sedimentation. The Figure 13.2 below shows the technical data such as mechanical properties of various Enkamat range.

Mechanical Properties	Test	Units	Enkamat® 7010	Enkamat® 7010	Enkamat® 7010	Enkamat® 7018	Enkamat® 7018	Enkamat® 7018	Enkamat® 7020	Enkamat® 7020
Polymer		kg/dm³	PA	PA	PA	PA	PA	PA	PA	PA
Weight	EN ISO 9864	g/m²	260	260	260	290	290	290	400	400
Thickness		mm	10	10	10	18	18	18	17	17
Tensile strength - MD	EN ISO 10319	kN/m	2.0	2.0	2.0	2.0	2.0	2.0	2.2	2.2
Tensile strength - CMD	EN ISO 10319	kN/m	1.5	1.5	1.5	1.2	1.2	1.2	1.6	1.6
Elongation at maximum load - MD	EN ISO 10319	%	110	110	110	80	80	80	80	80
Elongation at maximum load - CMD	EN ISO 10319	%	100	100	100	80	80	80	80	80
Static puncture resistance (CBR)	EN ISO 12236	kN	-	-	-	-	-	-	-	-
Dynamic perforation resistance (cone drc	EN ISO 13433	mm	-	-	-	-	-	-	-	-
Density		kg/dm³	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14
Temperature resistance		°C	-40/80	-40/80	-40/80	-40/80	-40/80	-40/80	-40/80	-40/80
Inflammability	DIN 4102		B2	B2	B2	B2	B2	B2	B2	B2
Structure Type			open	open	open	open	open	open	open	open
3 dimensional structure providing free volu		%	>95	>95	>95	>95	>95	>95	>95	>95
Soil retention factor		m/m²	1810	1810	1810	1290	1290	1290	1420	1420

Figure 13.2: Mechanical Properties of Enkamat Range

13.1.2 Application

Enkamat can be used in various erosion control applications as well a stabilization grip layer. It is available as an open mat for dry slopes where it is , or as a 'flatback' mat (with a flattended underside) for wet slopes and for use with stone chip fill where it is permanently submerged below the water level. Enkamat is also available sewn to a textile or fabric for diverse erosion control applications. On steep or rocky slopes and on smooth surfaces such as geomembranes, Enkamat is an effective and dependable grip layer that retains soil and supports protective vegetation.

13.1.3 Sustainability Aspects

Enkamat is a permanent erosion control solution.

13.1.4 Installation/Maintenance

Enkamat is a maintenance free reinforced turf mat.

For installation of the mat, it is to be laid on prepared ground and stapled into position ensuring good intimate contact with the soil. Seeding can take place during the soil filling or hydro seeding can be carried out after soil filling. However, installation process could be complicated on slopes with trenches. The laying process involves several steps including excavation, laying, backfilling the trenches, securing of overlaps, intermediate pinning, securing the edges, seeding and top soil filling. Further details of the laying guide could be in the installation guide brochure provided by Geofabrics, which is in [43].

13.2 Erosion Control Mat

TerraMat® is a three dimensional anti erosion mat consisting of entangled polypropylene mono filament fibres that are heat bonded to provide a dimensionally stable matrix to control soil erosion.

13.2.1 Function

It is designed to provide increased slope friction between low friction angle surfaces, permanent erosion control and reinforcement.

13.2.2 Application

It is suitable for grass and soil reinforcement. Applicable areas include steep embankment slopes, river banks, channels, coastal and other erosion prone areas.

Main advantages besides the previous listed edges and ends can be joined by lacing/hog ring to provide consistent strength in all direction required in steep slopes and high velocity streams.

13.2.3 Sustainability Aspects

Erosion control TerraMat uses double twisted zinc coated steel woven wire mesh.

13.2.4 Installation/Maintenance

Installation procedure varies depending on the slope and desired direction on installation. It is typically laid by beginning at the top of the slope and rolling the TerraMat® down slope.

As a general rule, if the degree of slope is greater than 1V:3H, it is recommended TerraMat® is rolled down the slope. For a degree of slope less than 1V:3H, the TerraMat® should be rolled across the slope.

Regardless of direction, to ensure effectiveness of the TerraMat® it is recommended that the upper edges on top of the embankment are secured in an anchor trench to resist lift and provide direct contact with the soil.

If more than one width is required it should overlap the TerraMat® previously installed.

Digging should be avoided on slopes to prevent further destabilisation. If the degree of slope is greater than 1V:3H it is recommended the anchor trench be installed at least 1m from the crest of the embankment.

Detailed procedure can be found in the installation guide provided by Polyfabrics, which can be found in [44].

13.3 Coir Mesh

Coir mesh is made from the fibres on the husks of coconuts. It retains moisture and prevents heat and wind from drying out the soil and causing erosion issues.

In coastal applications and areas where running water is a factor such as creeks and drains, coir matting offers excellent performance, providing a strong, long-term defence against erosion even in fast-flowing water.

13.3.1 Function

When vegetated, Coir mesh has the mechanical strength necessary to hold soil in place and prevent erosion. The coir netting slows down runoff from heavy rains and dissipates the energy of flowing water and wind.

13.3.2 Application

Application of coir mesh include erosion Control, slopes and soil Stabilisation. Common applicable areas include creeks and drains.

There are three grades available and the maximum water flow rate are 2.7 m/s, 3.8 m/s and 4.8 m/s.

13.3.3 Sustainability Aspects

100% nature coconut fibre and fully biodegradable

13.3.4 Installation/Maintenance

Coir mesh can be planted into or seeded into the soil, and maintenance is required to sustain vegetation only. However, coir mesh has only 2-4 years life span.

13.4 Concrete Mat

The concrete erosion mat is manufactured by Australian Concrete Mats and consists of concrete shapes, interlocked together and embedded into a high strength polyester geogrid.There are two versions of the concrete erosion mat: flexible or firm.

EARTHLOK is another manufacturer who makes flexible concrete matting system that consists of pyramid shaped 50 Mpa concrete block.

13.4.1 Function

The openings between the concrete shapes allows vegetation to grow through the mat.

Vegetation helps to anchor the mat and provides natural absorption and filtration of sediment into waterways.

The textured nature of the concrete shapes facilitates the slowing down of water as it travels across and around the shapes in the mat. This works especially well when the vegetation has grown through the geogrid spacings.

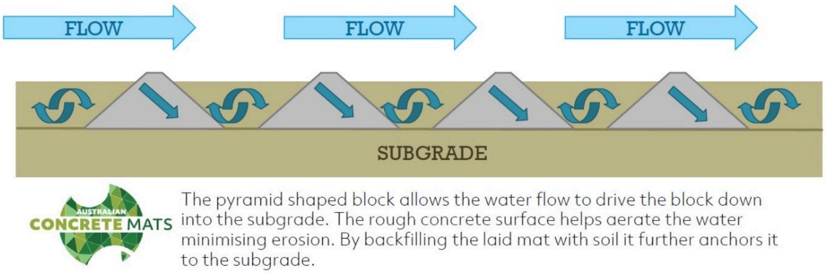


Figure 13.3: Concrete Mat function

13.4.2 Application

The concrete mat is most commonly used for erosion protection and prevention. The mats are used to protect swale drains, water channels, outlet protection, on slope stabilisation, for embankment protection, etc. The following figures show the specification of concrete mat products from two manufacturers.

Australian Concrete Mat & Roll Specs

MAT VERSIONS:	FLEXIBLE	FIRM
Material Weight (Approx)	45kg per m2	50kg per m2
Block Size (Approx)	160 x 148 x 58mm	160 x 148 x 58mm
Spacing between blocks	40mm	40mm

Concrete Mat Rolls Size and Weight Detail

WIDTH	LENGTH	6m	8m	10m	12m	15m
2400mm	FLEXIBLE CONCRETE MATS					
	Weight (kg)	648kg	864kg	1080kg	1296kg	1600kg
	Mats/Truckload 24t	37 Rolls	27 Rolls	24 Rolls	18 Rolls	15 Rolls
	FIRM CONCRETE MATS					
	Weight (kg)	720kg	960kg	1200kg	1440kg	1800kg
	Mats/Truckload 24t	33 Rolls	25 Rolls	20 Rolls	16 Rolls	13 Rolls
	STRAP AND ROLL SPECS					
	Lifting Points/Straps	2	2	2	2	2
	Diameter of each roll	Approx 40cm	Approx 60cm	Approx 70cm	Approx 80cm	Approx 90cm

Manufacturing Material Information

BLOCKS	INTERLOCKING GEOGRID
40 MPA, Wet-Cast portland cement, 6% Air entrained with 8mm Aggregate	40/40 mm Aperture Polyester Geogrid
	Ultimate Tensile Strength (ASTM D6637)
	Longitudinal 50KN/m
	Transverse 50kN/m

Performance Data

TEST	TEST VALUE	BED SLOPE	SOIL CLASSIFICATION	LIMITING VALUE
ASTM 6460	Shear Stress	0.3	Sandy Loam (USDA)	117 + kg/m2
ASTM 6460	Max Flow Velocity	0.3	Sandy Loam (USDA)	5.79 m/sec

www.ConcreteMats.com.au

ACM Specs - Mat Rolls & Lengths Rev11

Figure 13.4: Concrete Mat Specification from Australian Concrete Mats

General Composition of Materials	
Blocks	Concrete 50 MPA
Interlocking Geogrid	Flexible High Strength 60/60 kN Geogrid
Greenstar Rating	3 Stars
Underlay Options	Vegetative (biodegradable) Non Vegetative (non-biodegradable)
Concrete Colour	Can be coloured as requested
Manufacturing Values	
Roll Width	1.2m, 2.5m, 5.0m, Custom
Roll Length	15m, 20m, 25m, Custom
Material Weight	50kgs per Square Metre
Block Size	165mm x 165mm x 60mm
Performance Design Criteria	
Expected Design Life	50+ years Non Vegetative 100+ years Vegetative
Percentage Open Area	20%
Ultimate Tensile Strength	≥60 kN/m
Critical Flow Shear Stress for initiation of scour	≥1.149 kpa
Maximum Flow Velocity	≥5.79 m/s
Manning's n	0.05

Figure 13.5: Concrete Mat Specification from Earthlok

13.4.3 Sustainability Aspects

The concrete mat is estimated to have over 75 years life span.

13.4.4 Installation/Maintenance

The concrete mat is easy to unroll and install. Details can be found in ACM Installation Guide Flexible Concrete Mat in the manufacturer's website, Concrete Mats.

13.4.5 Case Studies

The concrete mat has been used in Wagga Wagga Solar Farm.

13.5 Articulated Concrete Blocks

The Articulated Concrete Cable Block Mat is a flexible concrete block revetment system specifically designed for permeable paving applications.

13.5.1 Function

It is designed to control various types of erosion due to water, wind or vehicular traffic.

The block mat system is interlocked by 16mm polypropylene or 8mm stainless steel cables, which are poured through each block in both directions.

13.5.2 Application

It has been used to stabilise slopes and prevent scouring of bridge abutment. It has also been used in low level creek, causeway and roads.

Figure 13.6: Articulated concrete block in application

13.5.3 Sustainability Aspects

It is expected that the articulated concrete block has longer life span than the concrete mat.

13.5.4 Installation/Maintenance

Anchoring is done using the following two methods. - Cable clamp to connect each mat to the next one (allow 5 per mat)

- Ubars straddling the cables (allow 4 per mat)

13.6 Geosynthetic Clay Liner

13.6.1 Function

Geosynthetic Clay Liners (GCLs) are an alternative form of scouring protection derived from the methodology of Geomembranes and Concrete Beds or Mattresses. They are commonly used to barrier from fluid lining the base or slopes of both landfills, canals and ponds. They're also notable for the effective ability to seal from fluid leakages and combat the erosive effects of flowing water.

13.6.2 Application

The purpose of GCLs are extendable from both industries to recreational employment. Ideally their relatively high shear resistance allows them to hold shape and prevent sliding of multiple layers. Therefore, making GCLs favourable for applications such as golf courses, ponds, dams, reservoirs, canals and landfills.

Mechanical Properties

Table 13.1: Mechanical Properties of Material – GCLs (Scouring)

Tensile Strength (kN/m)	Roll Length (m x m	Mass (kg/m^2)	Thickness (mm)	Internal Shear Strength (kPa)	Fluid Loss (mL)	Puncture Resistance (N)
2.54	22.5 to 30 (3.65 to 5.1 width)	>4.5	6	72	<16	2500

Feasibility
Low permeability and high strength allows this approach to be most effective and desirable within the protection of land and drainage pathways from scouring, erosion, and water flow. Furthermore, their capability to resist desiccation, differential subsidence, freeze-thaw, and root penetration allow them to be a valid candidate for the application of scouring protection. The calculation of leakage utilizing results from material studies and academic publications of GCLs denote a very low value in the order of 10^2)(-6) gpd/acre for a single square meter – calculated through Darcy's Law, clay samples and conversion factors. Moreover, the viability of GCLs against scouring protection can be evaluated through also investigating their alternative past range of applications such as;

- Municipal Wastewater Treatment Wetlands
- Septage Treatment Wetlands
- Municipal Stormwater Run-Off Containment & Filtration
- Wetlands Mitigation driven by Section 404 of the US Federal Clean Water Act]
- Wetlands for Waterfowl & Fishery Enhancement
- Riparian Corridor Enhancement
- Transportation Corridor Run-Off Control
- Estuarine Ecosystem Enhancement

13.6.3 Sustainability Aspects

Maintenance	Life Cycle	Carbon Emission in Production	Cost (AUD)
- For pond & heavy water use: Bentomat CL. - Cover material required prior to hydration. - Rarely requires replacement & will not become too wet. - Generates less dust when Granulated Bentonite GCL is utilized verses the Powdered Bentonite.	- Likely over 100yrs. - Resistant to freeze/thaw.	- 3.2 Truckloads compared to Conventional Clay Liner (CCL) 550 Truckloads - 34% reduction in carbon emissions during production compared to CCL	**$0.10** to **$0.25** per square meter. - Cost increase with needle punching and stitch bonding. - Factors such as shipping distance. - Size of the job. - Market demand. - Time of year.

Figure 13.7: Sustainability Aspects – GCLs (Scouring)

13.6.4 Installation/Maintenance

Overall process of installation is simplistic and can be summarized in the following steps: [45].

1. Storage
   - Store rolls within covered, dry area away from possible rainfall.
   - Prolonged storage is not recommended.
2. Subgrade Preparation
   - Subgrade must be properly prepared which involves removal of uneven surfaces; holes and obstacles.
   - Leveling of the surface to be relatively smooth.
   - Surface must be well-graded, firm, and unyielding subgrade – remove roots and rocks.
   - If subgrade is unsuitable, excavation, replacement & compaction is required for new material.
3. Anchorages Points & Trenches
   - Anchor trenches need to be created at the top of any slope steeper than a 1 vertical to 7 horizontal ratios.
   - Anchor trenches should be back-filled and compacted.
4. Roll Out
   - Panel layout should be done prior to installation

5. Overlap
    - Marking conventionally on rolls guide the overlapping and overall placement of either multiple rolls or cuts.
6. Secure Joints
    - Skin must be sealed with multiple layers of GCL around the penetration using Bentonite pate to bond each layer – for connections or around pre-existing structures.
    - There are multiple measures or approaches that can be employed to secure the clay such as:
        - Adhesives
        - Stitch bonding
        - Needle punching
        - Or a combination of the approaches.
7. Cover
    - Cover soil must be placed on top of the GCL.
    - Soil is to be spread evenly and not pushed under GCL overlaps.
    - Areas of high traffic or regular construction traffic, double thickness of cover soil may be required.
    - Avoid anything that may cause a penetration of the GCL.

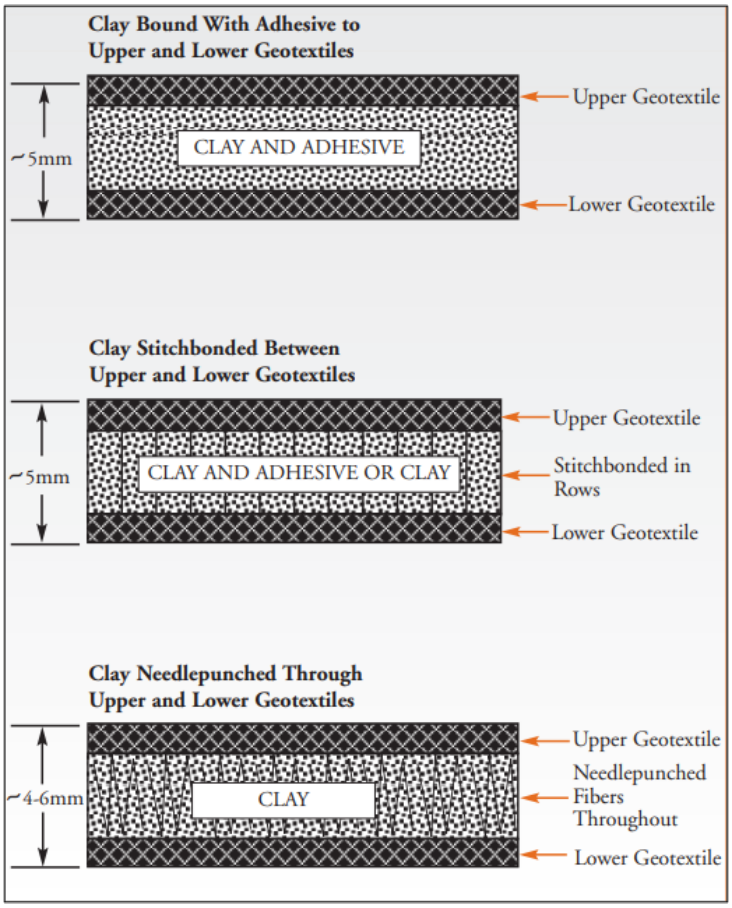


Figure 13.8: Affixing Bentonite to Geotextiles Visualisation

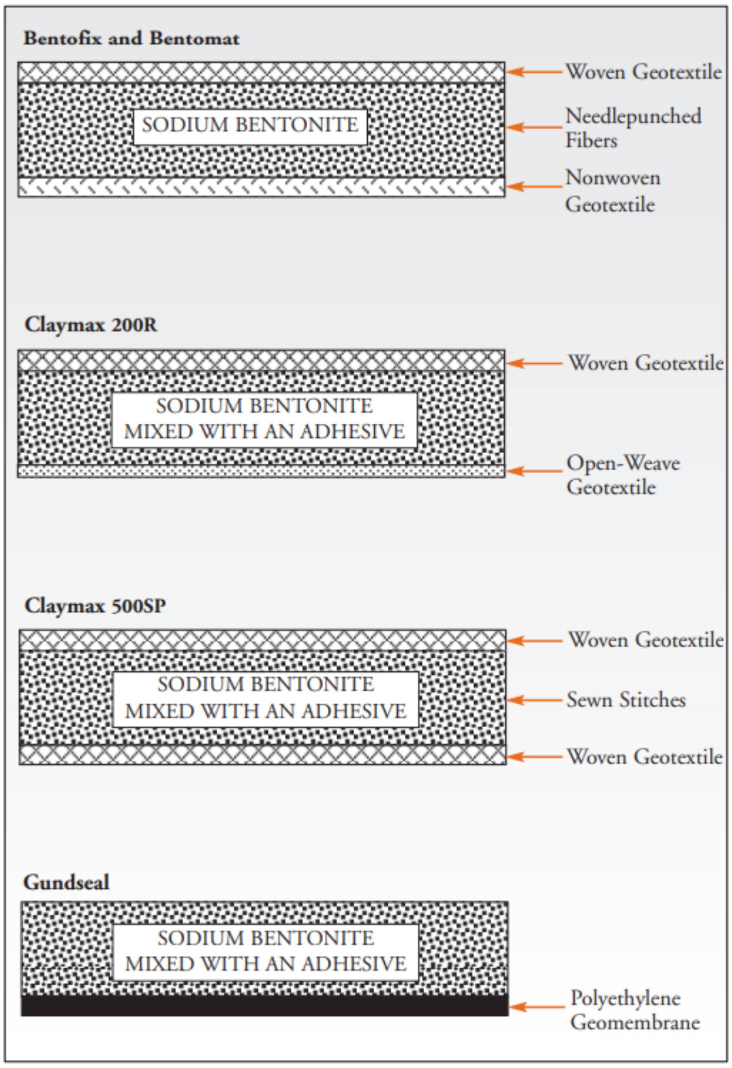


Figure 13.9: Available GCL Products & Layout

Implementation Costs

Within the implementation of GCL material and installation within a site, there are a range of documented common areas and processes that can inflate costs. Using the Bunbury-Harvey Regional Council documentation and report on Waste Disposal Options created by Talis we can isolate some of these unforeseen processes relevant within the stormwater system of solar farms and generate an estimate of costs other than the GCL product.

Table 13.2: Estimated Construction Cost using GCL (Scouring)

Item	Parameter	Unit	Rate ($)
Stormwater	Swale Construction (Perimeter Ditch)	(m^2)	$3.30
Capping	Supply & Install GCL Placement of Local Soil/Sand	m^2 & m^3	$15.00 & $1.50
Rehabilitation	Revegetation, Irrigation & Weed Spraying	-	$3.00

13.6.5 Case Studies

Celebration Park Wetlands
Approximately 17,200 square metres of GCL was used in drainage channel and detention ponds for a major sports complex in Federal Way, Washington. Detention ponds within this application are employed to filter stormwater and create wetland environments. Project was completed in 1998.

Mahwah NJ DOT Wetlands
Approximately 121,000 square meters of GCL was installed in a wetland's mitigation project along the Interstate 287 in Mahwah, New Jersey. A Geocomposite Drainage Blanket (GDB) was placed underneath the GCL in areas where free drainage of marsh water was needed. A geogrid was placed above the GCL so cover soil could be placed on top of the liner system using standard earthmoving equipment. The project was completed in 1994 after 18 months of construction (Trauger and Burgio, 1994).

Manufacturers
Most renowned manufactures and contractors associated with GCL products within Australia include:

- Bentotex GCLs
- Elcoseal GCLs
- Global Synthetics GCLs
- GC Labs

List of Complementing Products

Manufacturer & Product Name	Upper Geosynthetic[a]	Lower Geosynthetic[a]	Bonding Method	Standard Roll Width x Length (feet)
Fluid Systems, Inc. (FSI) (Germany)				
Bentofix NS	woven	nonwoven	needlepunched	(15.2 x 100)
Bentofix WP	woven	nonwoven	needlepunched	(15.2 x 100)
Bentofix NW	nonwoven[b]	nonwoven	needlepunched	(15.2 x 100)
Colloid Environmental Technologies Company (CETCO) (United States)				
Claymax 200R	woven	woven	adhered	(13.83 x 150)
Claymax 500SP	woven	woven	adhered and stitchbonded	(13.83 x 150)
Claymax 506SP	woven	woven	adhered and stitchbonded	(13.83 x 150)
Bentomat "ST"	woven	nonwoven	needlepunched	(15.3 x 125)
Bentomat "N"	nonwoven	nonwoven	needlepunched	(15.3 x 125)
GSE Environmental (United States)[c]				
Gundseal HD 20	none[d]	HDPE[e]	adhered	(17.5 x 200)
Gundseal HD 30	none[d]	HDPE	adhered	(17.5 x 200)
Gundseal HD 30	none[d]	HDPE/VLDPE[f]	adhered	(17.5 x 200)
Gundseal HD 60	none[d]	HDPE/VLDPE	adhered	(17.5 x 170)
Gundseal HD 80	none[d]	HDPE/VLDPE	adhered	(17.5 x 150)
Gundseal HD 40	none[d]	textured HDPE	adhered	(17.5 x 200)
Gundseal HD 60	none[d]	textured HDPE	adhered	(17.5 x 200)
Gundseal HD 80	none[d]	textured HDPE	adhered	(17.5 x 200)

[a] These properties vary by product and application.
[b] Nonwoven layer is scrim (a woven, open-mesh reinforcing fabric made from continuous-filament yarn) reinforced.
[c] All Gundseal products can be manufactured in 8-foot widths and with leachate-resistant bentonite. Products with backings that are 40 mils or greater can be manufactured with VLDPE as the lower geosynthetic material.
[d] Can be manufactured with a nonwoven, 0.75-ounce-per-square-yard geotextile as the upper geosynthetic material.
[e] High density polyethylene.
[f] Very low density polyethylene.

Figure 13.10: List of Complementing Materials & Products [46]

13.7 Geotextile Tubing

13.7.1 Function

A geotextile tube is a geotextile bag that is filled with a sediment slurry, its is made from a durable, porous fabric that allows water to escape when filled, whilst the sediment solid settles inside [47]. This results in a dense, monolithic structural mass [47]. Geotextile tubing can be made from polypropylene (PP) or polyethylene (PET) [48].

13.7.2 Application

Geotextile tubing is extremely durable. Geotube is able to withstand 828 N.m of force with minimal damage and no ruptures [47]. The mass of the geotextile and density of the sediment used have a significant effect on the tensile strength of the geotextile tube, with strength being greater with a geotextile of greater mass and a denser sediment [48].

13.7.3 Sustainability Aspects

Geotube TC1200 was predicted to lose 50% of its strength in 54 years in Southern Ontario [47], this would be greater in New South Wales, however it should last the 30 year life cycle of a solar farm and its life can be extended with special coverings using a base bag and coconut roll [49]. The geotextile tubes can be filled with sediment that has been dredged locally. This results in both lower costs and a lower carbon footprint as heavy materials do not have to be transported into the site from a distance [47].

13.7.4 Installation/Maintenance

As the sediment is locally sourced and heavy materials do not have to be transported into the site installation should be more feasible and less costly. Geotextile tubing has a base cost of \$950-\$1200/m [49]. Whilst there are no publicly advertised manufacturers of geotextile tubes in Australia, geotextile tubes could possibly be custom made from geotextiles. Manufacturers of geotextiles in Australia are Hudson Civil, Polyfabrics, Jaybro Group, Geofabrics Australasia, Geosynthetics Australia and Permathene.

13.7.5 Case Studies

One case study is for the Incheon Bridge in Korea [50]. Three different types of geotextile tubing were considered and stability against external forces was analysed at each cross section of the tube [50]. Wave force, tidal force and lateral earth pressure by reclamation were considered as external forces [50]. Before installing, scour aprons and base polyester mats were laid out on site and sandbags were placed on them to protect against currents [50]. 120mm diameter Post pipes were installed on the seabed that the geotextile tube could be fastened to, to ensure proper alignment during filling [50]. The sand was pumped in by flood tide in underwater or partially submerged conditions [50]. The geotextile tube was 50 m long and 5 m in diameter [50]. The slurry was 80% water and 20% sand [50]. The injection pressure was kept under 30 kPa to prevent potential rupturing of the tube [50]. A second, third and fourth layer were added on top as seen in Figure 13.11 [50]. While the earth pressure when fully injected was only 40% of what was predicted, the earth pressure under the 2nd layer was 130% of what was predicted due to load concentration on the centre line [50].

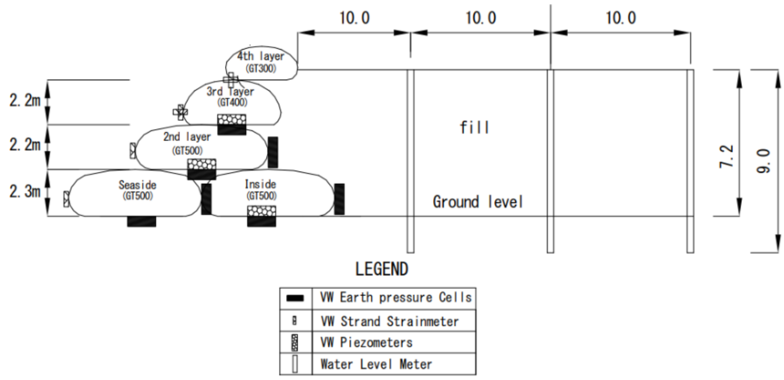


Figure 13.11: Configuration of Geotube [50]

Figure 13.12: Geotube [51]

13.8 Geocells

13.8.1 Function

Geocell is a lightweight three-dimensional Cellular Confinement System (CCS) made from High Density Polyethylene (HDPE). A CCS produces a new entity with enhanced mechanical and geotechnical properties when filled with compacted soils, vegetation or other local sourced sediments. When pressure is applied to the soil contained within a CCS, the cell wall experiences lateral stress. The three-dimensional confinement area restricts the movement of soil particles laterally. Geocell is an economical, flexible approach for soil stabilisation and erosion control, the effectiveness depends on the infilled materials.

Figure 13.13: Computational Model [52]

13.8.2 Application

Geocell has a wide variety of applications including rails, roads, coastal, mining, civic and landscaping, ports and aviation, slopes and walls aspects [52, 53].

- Channel Protection and Erosion Prevention: The hydraulic performance and erosion resistance of geocells can be improved by filling them with aggregate such as soil. Geocell is effectively used to enhance channel stability and reduce the effect of high pressure water, which can be applied to stormwater channels, channel lining and geomembrane protection.
- Slope and Embankment Stabilisation: The cellular configuration of geocell provides effective resistance to downward migration of soil and other slope materials caused by hydraulic flow events. The system also allows for vegetation growth, which prevents soil loss and improves the structural stability [53]. Additionally, for extremely demanding corrosion protection and stability, it can be achieved by installing non-woven geotextile.
- Rail and Roads Stabilisation: Geocells can be applied to rail and roads constructions in areas with soft subsoils to increase the stability and load bearing capacity of roadbed foundations. Besides, the three-dimensional configuration of geocells allows sufficient drainage.
- Pavement Stabilisation: Geocell can be implemented in areas with heavy traffic demands, high load capacity and soft subgrade soils in terms of both permanent and temporary use. The lateral resistance and service life can be improved in comparison to conventional pavement materials.

Manufactures: Geofabrics, Global Synthetics, Industrial Plastics

13.8.3 Sustainability Aspects

- **Environmental Impact:**
  Geocells provide a green solution that contributes to the sustainability of infrastructure products by reducing the amount of infill required for load support applications, thereby reducing pollution and carbon footprint. Geocells also provide environmental benefits by

reducing the amount of earthwork for engineering projects.

- **Carbon Emission of HDPE Materials:**
  The carbon footprint of HDPE is 1.60kg CO2/kg polyethylene [54].

- **Life Cycle:**
  It is a limitation of geocell product that the lifespan is approximately 20 - 25 years.

13.8.4 Installation/Maintenance

Geocell is in a folded configuration that help to minimize the transportation costs and can be readily expanded onsite for quick installation. During installation process, aggregate can be filled into geocells using a plate tamper. Geocells should be fully filled but not excessively over-filled [55].

13.8.5 Case Studies

Case Study 1:
Project: Hyden Wastewater Treatment Plant (Erosion Control)
Time Periods: October 2019 - January 2020
Location: Western Australia
Product: Miracell®
Manufacture: Global Synthetics
Project Description and Problem:
The Hyden Wastewater Treatment Plant (WWTP) provides the town of Hyden and surrounding agricultural regions with additional wastewater treatment capacity to accommodate current and future wastewater volumes. Previously, the external and internal slopes of the pond embankments at the Hyden WWTP were constructed using in-situ material with minimal erosion protection. Scouring has occurred over time as a result of storms and high winds in the region. Water Corporation was looking for a cost-effective, low-maintenance product for local scouring protection [56].

Solution:
Water Corporation authorised the installation of 100mm deep Miracell® CCS product, including anchor heads, connection keys, and structural Nylon tendons [56]. Nonwoven geotextile was also provided to separate the filled aggregate from the subgrade. Miracell® is a geocell product supplied by Global Synthetics that can provide scouring protection due to its enhanced hydrological and mechanical properties. The expansion of Water Corporation's WWTP will benefit from an innovative design utilising the CCS for long-term and economical containment and protection.

Case Study 2:
Project: Permeable Pavements
Time Periods: February 2017
Location: Springfield, SA
Product: GeoWeb

Manufacture: Geofabrics
Project Description and Problem:
Mitcham's Council was attempting to construct permeable pavement without compacting the soil in a tree-sensitive area. Keeping natural soils from being compacted while still allowing air and water to reach the soil and roots below without compromising the stability of the pavement is the goal [57].

Solution:
The Geoweb CCS was ultimately recommended as a solution by Geofabrics owing to its quick installation, proven strength and load bearing capacity over poor ground conditions. Infill aggregate is contained within Geoweb's cells, which reduces the stress on the moist subgrade and prevents the pavement from sinking [57]. In addition, Geoweb product allows the dry soil and roots beneath to be hydrated due to the porous screenings. A Megaflo flat panel drain was installed directly below geocells to allow even water distribution through the subgrade and adjacent pavements.

13.9 Geotextile Sand Containers

13.9.1 Function

Geotextile sand containers [58] are geotextile bags that are filled with sand like with geotextile tubes, however they small in size and are filled directly with dry sand and not dredged from a suspended slurry.

13.9.2 Application

As with geotextile tubes the mechanical properties are dependent on the geotextile used, the sediment used and the ratio of sediment used [58]. Secutex® Soft Rock has max tensile strength of 30.5kN/m after abrasion and a pressure resistance of 7.5kN [59], whilst TerraFix Soft Rock has has max tensile strength of 90kN/m after abrasion and a pressure resistance of 13kN [60].

13.9.3 Sustainability Aspects

As geotextile sand containers are filled with locally sourced sediment, heavy materials do not have to be transported into the site. This means that less pollution is produced in the installation process [59].

13.9.4 Installation/Maintenance

The fact that geotextile sand containers are filled with locally sourced sediment results in lower costs, as less is spent on materials, transportation and labour [59]. With a base cost of \$43 per m^2, manufacturers include Naue, Global Synthetics and Polyfabrics.

13.9.5 Case Studies

Geotextile sand containers have been manufactured and installed in a variety of forms in Australia since 1984 [61]. One example is the Maroochy River Groynes, constructed on the Maroochy River, Maroochydore, Queensland [61]. The project is a 50m long x 4m high groyne on the southern bank of the Maroochy River to stop erosion [61]. Two groynes were constructed over a height of 4 m using 1.2 m diameter tubes manufactured from polyester staple fibre needle punched geotextile as seen in the Figure 13.14 with the characteristics seen in Figure 13.15 [61]. After 6 years the groyne structures were performing to expectation.

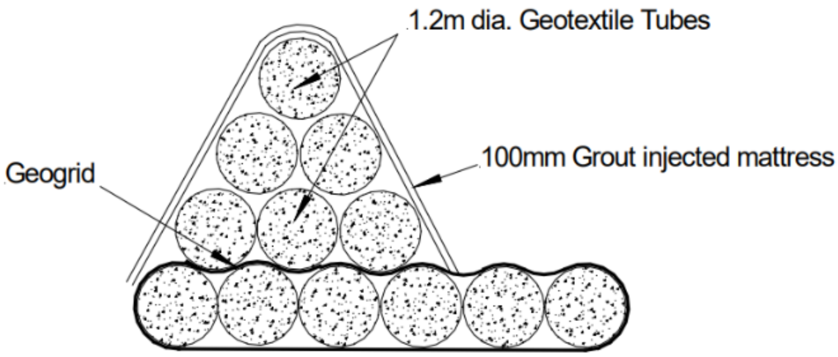


Figure 13.14: Section through groyne structure [61]

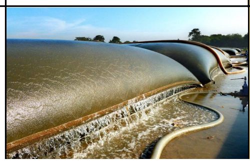
Table 3
Geotextile Tube Characteristics

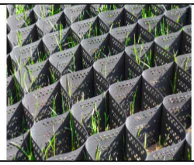
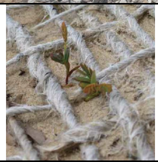
Thickness	CBR Burst	Tensile strength	Seam Strength
5.5mm	10 kN @ 60%	65kN/m XD 38kN/m MD	Min. 80% of base fabric

Figure 13.15: Geotextile Tube Characteristics [61]

Figure 13.16: Geotextile Sand Containers [62]

14 Evaluation Table for Scouring Optimisation

Criteria			Ease of Installation	Product Costs	Level of Scouring Protection	Maintenance	Environmental Impact
ID	*Options*	*Images*					
1	**Reinforced Turf Mat (Enkamat)**		**Laying on slopes with trenches involves: evacuation, laying and pinning, backfilling the trenhces, securing of overlaps, intermediate pinning, securing the edges, seeding, topsoil filling**	**$8.99/m2**	**Suitable (Permanent Erosion Control) Max Flow Velocity 2.2-3.9m/s**	**Maintenance free. Good resistance to weathering and radiation.**	**Low - Enkamat is inert & not harmful to the environment**
2	Erosion Control Mat (TerraMat)		**1670g/m2 Lay on from top and unroll down the slope, streches, secure with pins**	**$16.6/m2**	**Suitable for site with slope 1 - Max Flow Velocity: 2-6m/s different range of products 7.2m/s with vegetation**	-	**Steel Material**
3	Coir Mesh		**Light easy to unroll; anchor with sticks**	**$3.65/m2**	**Max Flow Velocity 4.8m/s**	**3-5 years Longetivity**	**Low**
4	Concrete Mat		**4500-5000g/m2; Easy to unroll and install**	**$37-38.5/m2**	**Max Flow Velocity 5.79m/s**	**Low**	**Concrete Material**
5	Articulated Concrete Blocks		**Laid out geotextile and put the mat on top**	**$150-432/m2**	**Max Flow Velocity 4.3m/s, 6m/s with Vegetation**	**Low**	**Concrete Material**
6	Geosynthetic Clay Liners		**Requires landwork, heavy machinary, storage and manual placement - roll out**	**$0.10-$0.25/m2**	**Tensile Strength: 2.54 - 14kN/m, Permability > 10^-12 to 10^-10 m/s**	**Low**	**Low-Moderate: Transportation, Landscaping**
7	Geotextile Tubing		**Sediment locally sourced, heavy materials don't have to be transported, installation more feasible, less costly**	**$950-$1200/m**	**Energy Resistance 820 N.m, Max Flow Velocity 22.22m/s**	**Low**	**Low - Transportation Demands**

8	Geocells		Flexible to fold during transportation and easy installation - applicable to different soil types	$4.95/m2 or $9.43/m2 - depending on grading	3-6m/s depending on the infill materials. High erosion control capacity	20 - 25 years	Minimal: HDPE - Geocells offer a green solution that adds sustainability, reduces the amount of infill, in turn reduces the pollution & carbon footprint
9	Geotextil Sand Containers		Sediment locally sourced, heavy materials don't have to be transported, installation more feasible, less costly.	$43/m2	Max Flow Velocity 2.5m/s, Tensile Strength: 7.5-13 kN	Low	Low - Transportation Demands
10	Rock Lined Channels		Moderate	$61.75/m3 (installed) with Geofabric requirement $2-$4/m2	Acceptable - Sufficient for sites with rock sizes to suit energy requirements for velocities & grades. Maximum Flow Velocity 0.5-5m/s	Low	Moderate - Transportation Demands, Excavation & Environment Deformation
11	Jute Mesh		Simple roll out application	$0.70/m2 + installation costs approx. $5/m2 + grass seeding	No Acceptable - Product to stabalise initial grass only, Maximum Flow Velocity 1.3-1.7 m/s	Potential maintenance after storm events	Low - Transportation Demands Soil/grass minimally disturbed
12	Jute Matting Fine		Simple roll out application	$1.50/m2 + installation costs approx. $5/m2 + grass seeding	No Acceptable - Product to stabalise initial grass only, Maximum Flow Velocity 1.8m/s	Potential maintenance after storm events	Low - Transportation Demands Soil/grass minimally disturbed
13	Grassroots		Moderate	$7.00/m2 (product) + $7.00/m2 (installation)	Max Flow Velocity 7m/s	7 years design life. Maintenance & re-installation may be required. First 7 years. Channel will have established grass, however potential maintenance after storm events.	Grass & channel system considered well established after 7 years.
14	Reno Mattress		Intensive Installation process. A 5 person team can install 100 units per day - 22 working day installation	$100 per unit (approx.)	Max Flow Velocity 3.5m/s Acceptable - Sufficient for sites of 0.17m & rock sizes of 70-120mm	Low	Soil Impact & Low Sustainable regard within production process.

15	GeoWeb		**Intensive Installation process**	**$15-20/m2 (product), $30-40/m2 (installation) & stone or soil + turf cost**	**Acceptable - sufficient for the site with depth & rock. Sizes to suit energy requirements for the velocities & grades. Maximum Flow Velocity 9m/s**	**Low**	**Low**
16	Concrete Canvas		**Minimal to medium - simple installation for a robust product**	**$70.00**	**Maximum Flow Velocity 6m/s**	**Low**	**Moderate - Transportation Demands, Excavation & Environment Deformation**

15 Proposed Solution(s) for Scouring Control

15.1 Geocells

15.1.1 Benefits

- Low handling cost: Geocell is a light-weight material that can be folded flat and stored on pallets, which contributes to minimising the transportation cost.
- Low labour cost: Easy and quick installation process. Equipment such as crane-mounted skips or excavators can be utilised in order to reduce the labour needed and the corresponding construction time and cost.
- Low maintenance and subsequent costs.
- Geocells can provide sufficient tensile strength, stability and load bearing capacity for permanent erosion control.
- Geocell is flexible to different soil types and has a wide variety of applications including rails, roads, coastal, mining, civic and landscaping, ports and aviation, slopes and walls aspects.

Cost

Cost quotation for CCS Geocell from Industrial Plastics is listed in the table below:

Table 15.1: Unit Cost of Geocells from Industrial Plastcs

Product Description	Unit of Measure (UOM)	Unit Price + Goods and Services Tax (GST) ($)
HDPE Geocell - 50mm cell depth	m^2	4.95
HDPE Geocell - 100mm cell depth	m^2	9.43

Sustainability

- **Production:** Geocells are made of HDPE material, which is an eco-friendly material with carbon footprint of 1.60kg CO2/kg.
- **Transportation:** Geocells are in folded configuration that minimises the transportation costs and corresponding carbon emissions into the atmosphere. The infilled material can be local sourced or vegetation, which also reduces negative impacts on the environment.
- **Construction:** Geocells can be easily expanded on site and reduces environmental pollution caused by utilising large-scale construction machines or vehicles. Geocells offer a green solution that adds sustainability to infrastructure products by reducing the amount of infill needed to reinforce load support applications which in turn reduces the pollution and carbon footprint.

15.1.2 Limitation

Lifespan of geocell product is relatively low, which is approximately 20 - 25 years.

15.1.3 Applications in Solar Farms

Geocell products can be implemented in solar farms for permanent scouring protection and erosion control owing to the outstanding hydrological, structural performance, sustainability and cost-effectiveness. The maximum flow rate that can be resisted varies from 3 m/s to 6 m/s, depending on the infill materials.

15.2 Geotextiles in Sand Container

15.2.1 Benefits

Geotextile sand containers are filled with locally sourced sediment, heavy materials do not have to be transported into the site. This results in both a reduction of cost and pollution in the installation process.

Cost

\$43 per m²

Sustainability

As geotextile sand containers are filled with locally sourced sediment, heavy materials do not have to be transported into the site. This means that less pollution is produced in the installation process [59].

15.2.2 Limitation

Geotextile sand containers are relatively expensive compared to other solutions, and are generally only suitable where significant scouring protection is required.

15.2.3 Applications in Solar Farms

Geotextile sand container would most likely be used on solar farms with large creeks on them, where significant scouring protection is required.

15.3 Reinforced Turf Mat

15.3.1 Benefits

- **Cost-effectiveness:** Enkamat mat is claimed to be maintenance free, which makes the mat is to be very cost-efficient compared to other solutions.
- **Sustainability:** The mat is a permanent erosion control solution. It is inert and not harmful to the environment and has been approved for use in potable water reservoirs.

- **Mechanical Properties:** Enkamat has over 90% soil holding capacity. The tough filament core structure which has >95% open voids is unique to the mat, as this allows soil to be contained within the mat effectively preventing it from being eroded away by rain or wind. The mat also has a maximum soil retention factor of 1810 m/m^2 and creates an artificial root structure by its high filament density – up to 2980m filaments per squared meter. Further details such as tensile strengths and elongation at maximum load could be found in Figure 13.2 in Section 13.1.1.

- **Durability:** Enkamat provides high resistance to weathering and UV radiation and has low flammability. It is also known to be resistant to all chemicals in concentrations which are normally contained in the earth and surface water. The mat is also known to be light, felxible and does not float in water.

- **Other advantages:** 3D open structure encourages swift vegetation growth and reinforces vegetation root systems. The mat blends discretely into the landscape and remains locked to the ground by root system.

15.3.2 Limitation

One of the limitations of the mat is to have a slightly complicated laying process on slopes with trenches. The laying process involves several steps including excavation, laying, backfilling the trenches, securing of overlaps, intermediate pinning, securing the edges, seeding and top soil filling. Further details of the laying guide could be in the installation guide brochure provided by Geofabrics, which is in [43]. Another limitation is the product cost is higher than other solutions such as coir mesh and geosynthetic clay liner.

Product cost per squared meter: 18mm thick, 1.95x120m roll at **\$8.99/m^2**.

15.3.3 Applications in Solar Farms

Enkamat can be used in various erosion control applications as well a stabilization grip layer. It is available as an open mat for dry slopes where it is , or as a 'flatback' mat (with a flattended underside) for wet slopes and for use with stone chip fill where it is permanently submerged below the water level. Enkamat is also available sewn to a textile or fabric for diverse erosion control applications. On steep or rocky slopes and on smooth surfaces such as geomembranes, Enkamat is an effective and dependable grip layer that retains soil and supports protective vegetation.

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Appendices

A Weather Conditions during Testing

	Date/Time EST	Temp °C	App Temp °C	Dew Point °C	Rel Hum %	Delta-T °C	Wind Dir	Wind Spd km/h	Wind Gust km/h	Wind Spd kts	Wind Gust kts
Badgerys Creek (12.23km NW of site)	18/04:30	11.8	7.4	0.3	45	4.8	WSW	13	20	7	11
	18/04:00	12.8	7.6	0.2	42	5.2	SW	17	24	9	13
	18/03:30	13.5	8.4	0.5	41	5.5	WSW	17	22	9	12
	18/03:00	13.5	7	0.5	41	5.5	WSW	24	32	13	17
	18/02:30	14	7.3	1.6	43	5.4	WSW	26	33	14	18
	18/02:00	14.4	8.7	0.6	39	5.9	WSW	20	30	11	16
Campbelltown (13.40km SSW of site)	18/04:30	12.3	8.1	-0.9	40	5.4	W	11	20	6	11
	18/04:00	13.3	9.2	-0.3	39	5.6	W	11	20	6	11
	18/03:30	13.7	9.6	-0.3	38	5.8	W	11	20	6	11
	18/03:00	13.6	9	-0.8	37	5.9	WSW	13	26	7	14
	18/02:30	13.9	8.8	-1.7	34	6.3	W	15	26	8	14
	18/02:00	13.9	8.9	-1.3	35	6.2	SW	15	30	8	16
Holsworthy (10.28km ESE of site)	18/04:30	12.9	8.2	-1.8	36	5.9	W	13	19	7	10
	18/04:00	13.4	8.3	-2.1	34	6.2	WSW	15	22	8	12
	18/03:30	14	9	-1.2	35	6.2	WSW	15	24	8	13
	18/03:00	13.9	8.3	-2.9	31	6.6	W	17	32	9	17
	18/02:30	14.2	8.6	-2.7	31	6.7	WSW	17	32	9	17
	18/02:00	14	8	-1.6	34	6.3	W	20	33	11	18
Horsley Park (11.90 N of site)	18/04:30	12.7	9	-0.2	41	5.3	SW	9	15	5	8
	18/04:00	12.9	9.4	-1.4	37	5.8	SW	7	13	4	7
	18/03:30	13	8.5	-0.6	39	5.6	WSW	13	24	7	13
	18/03:00	13.6	8.8	0.3	40	5.6	WSW	15	30	8	16
	18/02:30	14	8.6	-1.2	35	6.2	WSW	17	28	9	15
	18/02:00	13.9	8.6	-0.5	37	6	WSW	17	30	9	16
Average	18/04:30	12.425	8.175	-0.65	40.5	5.35	WSW	11.5	18.5	6.25	10
	18/04:00	13.1	8.625	-0.9	38	5.7	WSW	12.5	19.75	6.75	10.75
	18/03:30	13.55	8.875	-0.4	38.25	5.775	WSW	14	22.5	7.5	12.25
	18/03:00	13.65	8.275	-0.725	37.25	5.9	WSW	17.25	30	9.25	16
	18/02:30	14.025	8.325	-1	35.75	6.15	WSW	18.75	29.75	10	16
	18/02:00	14.05	8.55	-0.7	36.25	6.1	WSW	18	30.75	9.75	16.5

Figure A.1: Weather Conditions

B Material List for the Experiment

ACTIVITIES/DELIVERABLES	SIZE	COST	AMOUNT
Synthetic Grass	13m 18mm Thickness	$39	2
Hose Head	13mm	$20.47	2
Hose Splitter	12mm	$7.91	1
Hose	12mm15m	$6.50	3
Plastic Cellular Sheeting	0.91.2m	$89.43	1
Polycarbonate Sheet	0.611.2m 8mm Height	$24.60	1
Sloped Guttering	2.4m (Length) 0.10.06m	$23.25	1
Container	7L	$24.09	1
Measuring Containers	1-2L	-	2
Plastic Material	25m	$21	1
Waterproof Tape	-	-	1
Drainage Cell	11m 30mm Thickness	$22.55	2
Stand	-	$80	1
Garden Blower	-	-	1
Drying Cloth	-	-	1
Hose Control Valve	-	$21.25	2
Weight Scale	-	-	1

Stanley Knife	-	-	1
Protractor	-	-	1
Tape Measure	3m	-	1
Level	-	-	1
Table	0.91.8m	-	1
TOTAL SPENT			

C Input Data and Resulting Data

Rainfall Intensity = 1.17 mm/min		Rainfall Running Stage																			
		1 min				2 min				3 min				4 min				5 min			
Dependent Variables	**Time (s)**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**
Pre-installation (No Panels)	**Surface Runoff Weight (g)** With Edge Guards	10	23	41	56	69	92	117	144	178	218	265	308	352	379	438	495	560	628	693	769
	Surface Runoff Weight (g) Without Edge Guards	17	37	66	90	129	168	213	254	303	372	438	495	567	630	704	781	894	1041	1171	1302
25-degree	**Surface Runoff Weight (g)** With Edge Guards	23	48	81	118	158	194	260	334	427	547	683	845	982	1126	1260	1415	1560	1783	2047	2306
	Surface Runoff Weight (g) Without Edge Guards	12	33	50	77	118	153	189	248	339	446	590	738	898	1053	1236	1394	1559	1716	1871	2037
35-degree	**Surface Runoff Weight (g)** With Edge Guards	17	32	48	63	85	107	128	151	180	218	261	307	368	421	518	558	637	717	793	884
	Surface Runoff Weight (g) Without Edge Guards	7	18	32	45	60	79	94	124	146	178	223	265	319	372	475	619	NA	631	751	899
45-degree	**Surface Runoff Weight (g)** With Edge Guards	18	39	63	98	128	150	182	213	247	280	324	367	416	467	534	623	663	753	848	957
	Surface Runoff Weight (g) Without Edge Guards	17	36	55	74	97	126	151	173	191	223	251	296	341	413	516	NA	571	687	828	958

Rainfall Intensity = 1.17 mm/min		Rainfall Halted Stage																			
		1 min				2 min				3 min				4 min				5 min			
Dependent Variables	**Time (s)**	**315**	**330**	**345**	**360**	**375**	**390**	**405**	**420**	**435**	**450**	**465**	**480**	**495**	**510**	**525**	**540**	**555**	**570**	**585**	**600**
Pre-installation (No Panels)	**Surface Runoff Weight (g)** With Edge Guards	815	895	957	1018	1078	1138	1193	1248	1302	1353	1405	1448	1499	1537	1576	1616	1652	1686	1720	1761
	Surface Runoff Weight (g) Without Edge Guards	1429	1535	1638	1718	1793	1870	1942	2004	2058	2112	2165	2177	2225	2271	2321	2355	2392	2425	2462	2496
25-degree	**Surface Runoff Weight (g)** With Edge Guards	2354	2474	2561	2650	2722	2790	2854	2908	2966	3009	3059	3113	3139	3187	3220	3249	3281	3312	3342	3370
	Surface Runoff Weight (g) Without Edge Guards	2190	2219	2316	2423	2527	2613	2688	2758	2813	2873	2926	2980	3019	3059	3097	3131	3166	3197	3235	3265
35-degree	**Surface Runoff Weight (g)** With Edge Guards	970	1062	1128	1148	1259	1311	1361	1409	1453	1493	1539	1583	1615	1651	1687	1722	1747	1778	1806	1833
	Surface Runoff Weight (g) Without Edge Guards	911	1044	1164	1273	1354	1429	1502	1561	1618	1667	1707	1740	1775	1804	1831	1857	1881	1901	1927	1951
45-degree	**Surface Runoff Weight (g)** With Edge Guards	1068	1180	1278	1369	1451	1530	1601	1668	1728	1784	1831	1885	1925	1973	2012	2063	2107	2155	2188	2222
	Surface Runoff Weight (g) Without Edge Guards	1110	1244	1374	1486	1574	1650	1721	1784	1834	1885	1927	1967	2008	2049	2091	2110	2140	2159	2174	2189

D Calculation of Panel Catchment - Placement at Top of Setup

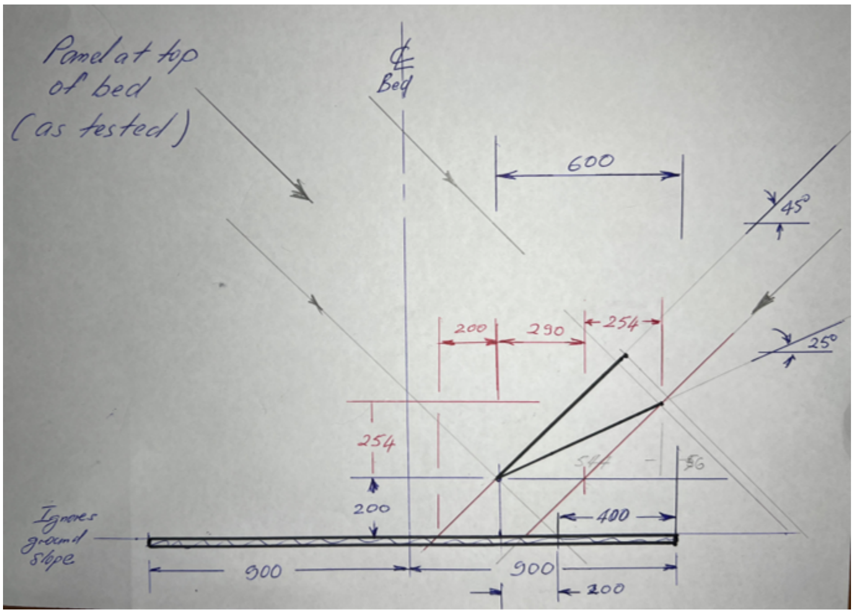

Figure D.1: Geometric Calculations of Panel Catchment - Panel placed at Top of Setup

E Calculation of Panel Catchment - Panel at Middle of Setup

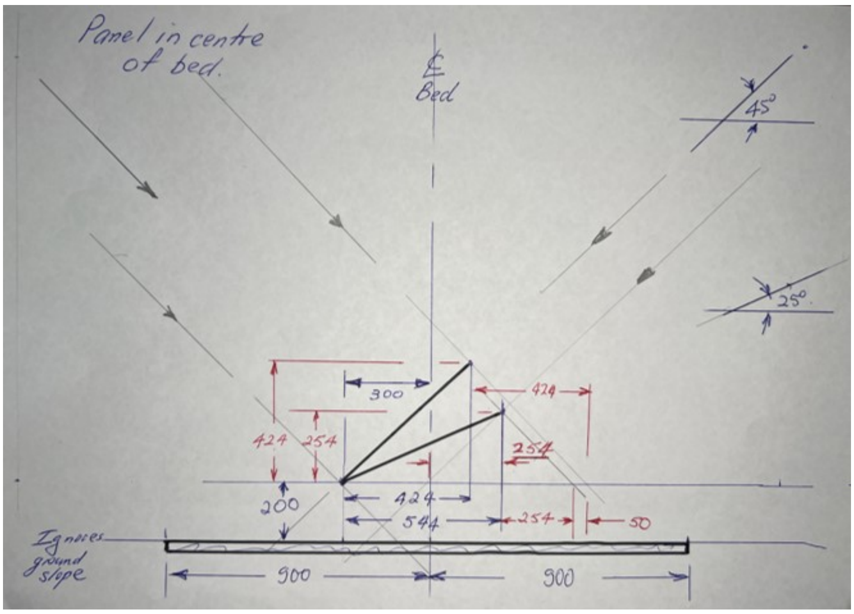

Figure E.1: Geometric Calculations of Panel Catchment - Panel placed at the Middle of Setup