

Implications of Sea Level Rise on Coastal Pavement Infrastructure for the Funafuti Airport Runway (Tuvalu)



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Quality Assurance Statement	
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Executive Summary

Airports are critical infrastructure to all countries as they connect us to the rest of the world for travel, commerce as well as connecting to family with ever-increasing globalisation. Airports are even more relevant to many Pacific island countries such as Tuvalu since they not only connect the island for the normal travel needs, but they are also a link to work opportunities and medical care that are not available on the islands. This report investigated the impact of sea-level rise on coastal infrastructure with a specific emphasis on airport pavements.

The purpose of this research is to understand the impact of groundwater and tides on coastal pavement infrastructure with a specific study on the Funafuti airport runway. To achieve this purpose, the following objectives have been defined:

- i. for the damaged runway and apron undertake detailed measurements and investigations of sub-surface barometric pressures, groundwater levels and pavement properties, etc. to confirm the impact of tidal level fluctuations and potentially associated barometric pressures on the pavement;
- ii. to provide a framework to identify appropriate investments where these risks exist; and,
- iii. propose design solutions to address the site-specific risk for Tuvalu, and to extend this to provide guidelines for future airfield investment projects in similar low-lying Pacific atoll environments.

A review of international publications and practices has revealed the following:

- The mechanisms of water movement below Atoll Islands are well documented and understood;
- Evidence of increasing extreme tidal levels on Tuvalu does exist, although the predictability of these increases is an extremely complex topic area;
- There have been some documented case studies of similar occurrences, most notably from the Hong Kong airport runway and some cases in Australia. The Australian experience resulted from extreme rain events than any tidal influence; and,
- Publicised remedial work for the blistering effects is limited to the Hong Kong case study;

The instrumentation of the Funafuti Runway (3- 7 March 2017) included:

- Excavation of two test pits adjacent to the side of the runway to a refusal depth of 1.4m;
- Installation of a single 32mm dia. PVC standpipe within each pit (BH1-2) to a depth of 1.4m below ground level;
- Installation of a levellogger within each PVC Standpipe to monitor groundwater levels;
- Coring four additional test excavations through the airport runway and taxi apron to a depth of 0.2m; and,
- Installation of a vapour pressure logger within each cored holes with a direct read cable to read the information outside the runway apron to record vapour pressures under the airport pavement.

The instrumentation monitoring was carried out over three months. The measurements indicated the following:

- There is a correlation between water table levels and the sea tidal fluctuations;
- There is a correlation between sub-surface pressure and the measured water table;
- The correlation between the sub-surface pressure and the temperature were consistent with the prevailing atmospheric pressure thus not showing a significant trend; and,
- None of the above-mentioned trends causes sufficient vapour pressure to lift the pavement surface, but there were some spikes noticed in the procurement measurement that could cause excess pressure sufficient to lift the pavement surface. Further analyses suggested a definite link between the pressure

spikes with the water table and/or tidal fluctuation. There is also weak correlation with the coinciding occurrence of high tides and rainstorms.

Recommended remedial work options are summarised in the table.

Option	Description	Cost Estimate (Million)
Base Line –not to resurface	It is not recommended to consider a re-surface at this point before drainage aspects have been constructed. There is a significant risk of water still penetrating through the first surface layer. Delamination of the new surface would be unavoidable.	Included to options below
Base Line – Cut-off Drains	Install cut-off drains on both sides of the runway in location where failures are occurring	Included to options below
Short Term Option	Install vertical venting drains as part of the patching strategy to prevent the formation of new venting paths. A similar design to that of the Hong Kong case study is recommended	\$1,767
Medium-term Option	Install herringbone subsurface drainage in affected/high-risk areas. If possible, horizontal drilling should be considered as a cost-effective option. A priority drainage zone would include at least 1/3 of the length of the runway and include 2/3 of the width of the runway (1/3 on both sides)	\$7,837
Long-term option	Install herringbone subsurface drainage using a trenching method and reconstruct base course. This option has to consider a more permeable surfacing option.	\$8,612

The preferred option would be to install sub-surface fish bone type drainage system using a directional drilling technique. That way the current base course and surface does not have to be replaced. However, the final option will depend on engineering assessment of the integrity of the current base course.

Further recommendations include:

- Widely publicise the outcome of this study in official bank publications and to a wider audience;
- Include recommended monitoring regimes of fluctuating water tables and vapour pressure monitoring as a standard pre-design data collection item to the Terms of Reference for future projects;
- Include continuous rainfall measurement on the island;
- Monitor the effectiveness of the implemented solution for the Funafuti runway; and,
- Undertake further research into developing durable permeable surfaces.

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Implications of Sea Level Rise on Coastal Pavement Infrastructure

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1. Introduction

1.1 Background

Airports are critical infrastructure to all countries as they connect us to the rest of the world for travel, commerce and connect us to family in an ever-increasing globalisation. Airports are even more relevant to many Pacific island countries such as Tuvalu since they not only connect the island for the normal travel needs, but are also a link to work opportunities and medical care that are not available on the islands. This report investigated the impact of sea-level rise on coastal infrastructure with a specific emphasis on airport pavements.

Airport runways require long, flat terrain, something that is not easy to find on many small atoll islands. For this reason, reclaiming some areas of sea water and swampy areas is a common practice for the construction of runways. Being in such proximity to water or historical swamp areas often creates recurring challenges for engineers. Dealing on top of that with rising sea level aggravates the issues and dealing with it is often outside the scope of normal engineering design considerations.

Although this report was written primarily with the aim of understanding and resolving the issues experienced on the Funafuti airport, it considers future design investigations and construction practices in dealing with the issues on coastal infrastructure that are and will be subjected to sea level rise.

1.2 Objectives of the Report

The purpose of this research is to understand the impact of sea level rise and groundwater on coastal pavement infrastructure with a specific study on the Funafuti airport runway. To achieve this purpose, the following objectives have been defined:

- iv. for the damaged runway and apron undertake detailed measurements and investigations of sub-surface barometric pressures, groundwater levels and pavement properties, etc. to confirm the impact of tidal fluctuations and potentially associated barometric pressures on the pavement;
- v. to provide a framework to identify appropriate investments where these risks exist; and,
- vi. propose design solutions to address the site specific risk, and to extend this to provide guidelines for future airfield investment projects in similar low lying Pacific atoll environments .

1.3 Scope

The specific scope of this project included the following two phases:

Phase 1: Pavement Testing

1. Review of all reports available related to the paving of Funafuti, including the original pavement condition report, the detailed design and the testing results from the contractor during construction;
2. Investigate other similar failures elsewhere;
3. Develop a detailed testing regime to confirm the cause of the pavement failure including:
 - a. Installation of piezoelectric sensors and other instruments at Funafuti to record data continuously (24 h/day; 7 days/week) over a period of three months.
 - b. Consider past destructive and non-destructive tests as appropriate to accurately quantify the nature of the pavement and identify all potential modes of failure.
 - c. Appropriate laboratory tests, including on the properties of the bitumen, tack coat, and other elements.

Phase 2: Data Analysis and Interpretation

1. Based on the data collected in Phase 1 investigate the cause of the pavement failure.
2. Depending upon the mode of failure, recommend:
 - a. What tests should be undertaken during design to identify the risks of failure
 - b. Specific construction techniques to prevent such failures
 - c. Options for retrofitting to existing infrastructure to address the failure

2. Climate Change and Tidal Patterns Impacts on Atoll Islands

2.1 Changing Sea –Levels Tidal Patterns

Understanding the changing tidal patterns for the Polynesia region is complex scientific topic matter. The perceived principal risk for the Pacific region in response to Climate change effects is sea-level rise, but in fact, that is an over-simplification of the issues impacting the region. There is an array of considerations of oceanic patterns in addition to sea-level rise including increasing tidal level, storm frequency and wave levels. Also, sea-level rise effects are region specific as some of the changes would be influenced by (Lin et al., 2014):

- Isostatic rebound;
- climate variability;
- non-uniform changes in ocean thermal expansion and;
- warm-water effects.

The sea-level rise increase recorded for Tuvalu is approximately 5mm per year since 1993, which is more than the recorded 2.8-3.6 mm/year estimates on a global level (ABoM and CSIRO-Vol 2, 2011). Although seemingly minor, this change has a drastic impact on other oceanic patterns, none of which is stronger felt by Tuvaluans than the tidal patterns. The report on “Climate Change in the Pacific: Scientific Assessment and New Research” also presented the tidal fluctuations between 1950 to 2010, as presented in Figure 2.1 (ABM and CSIRO-Vol 1, 2011). Although Tuvalu does not have the highest tidal level, it is alarming to note the steady increase over time. Other regions such as Tonga had a relatively flat trend in tidal level for the most part of the recorded period, but a sharp increase over recent years.

Another aspect that needs consideration is the king tide and spring tide events. According to the United States Environmental Protection Agency (EPA): “*King tide is the highest predicted high tide of the year at a coastal location. It is above the highest water level reached at high tide on an average day. King tides are also known as perigean spring tides*”¹. Figure 2.2 illustrates the gauge recorded spring tides that have occurred in Tuvalu during a four-month monitoring period in 2011. During this period a total of six tide levels exceeded the RL 3.2 m tidal mark. Figure 2.3 shows how the spring tide levels are related to the airport runway. The runway is highlighted by the oval shape, at this particular location the ground level is very close to (below on the shoulders at the damage zone) the spring tide level. Field observations have confirmed that for some areas the ground level would even be below the spring tide levels and well below king tide levels. Section 4.3 details some ground water level measurements that were undertaken as part of this study.

¹ See EPA Website <https://www.epa.gov/cre/king-tides-and-climate-change>

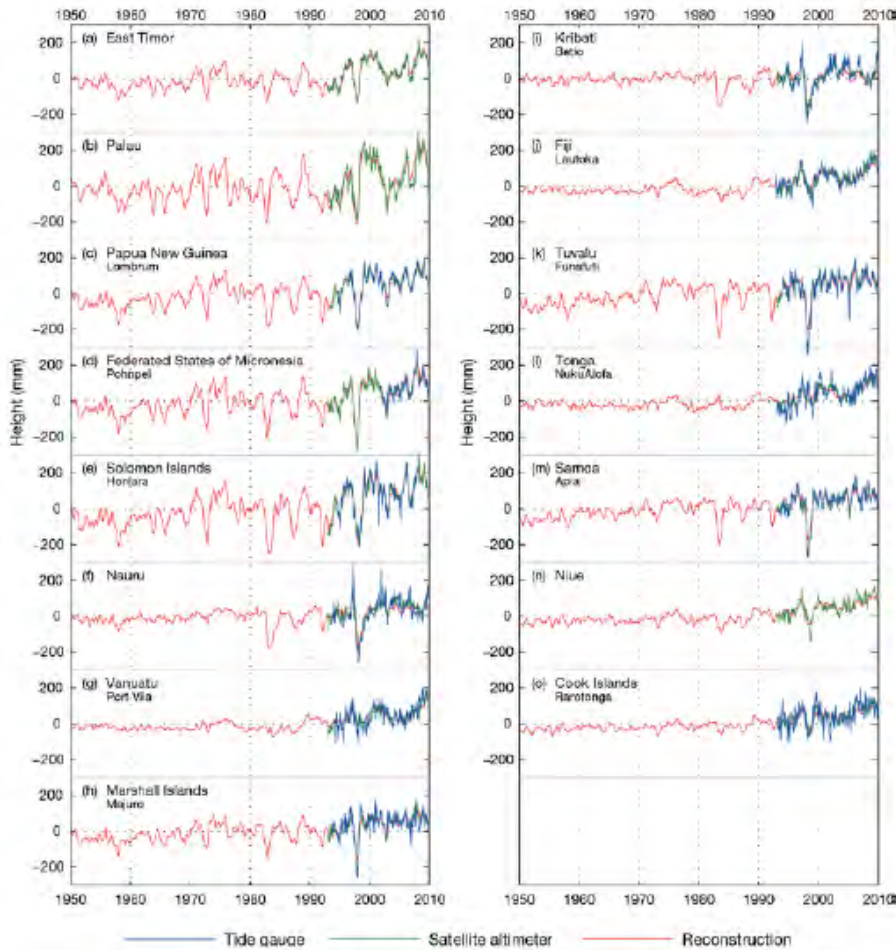


Figure 2.1: Time series of monthly tide gauge data (blue) with satellite altimeter data (green) and reconstructed sea levels (red) (ABM and CSIRO-Vol 1, 2011)

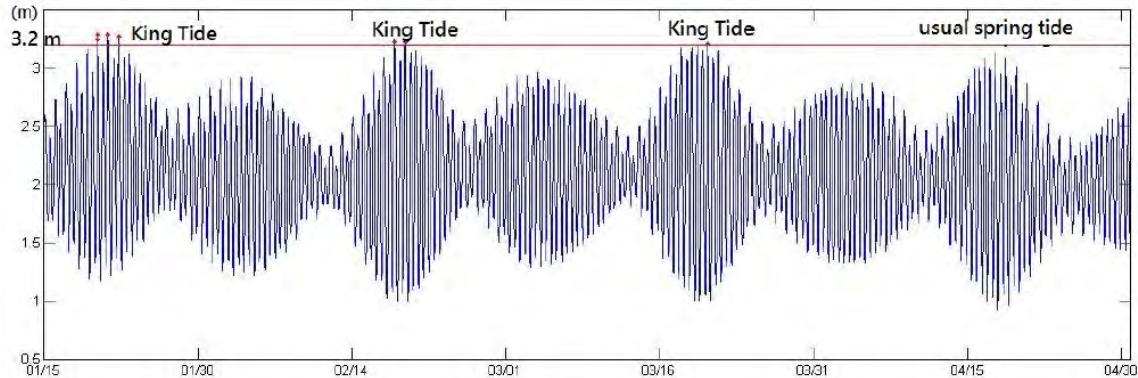


Figure 2.2: Tidal Patterns During 2011 (Lin et al, 2014)

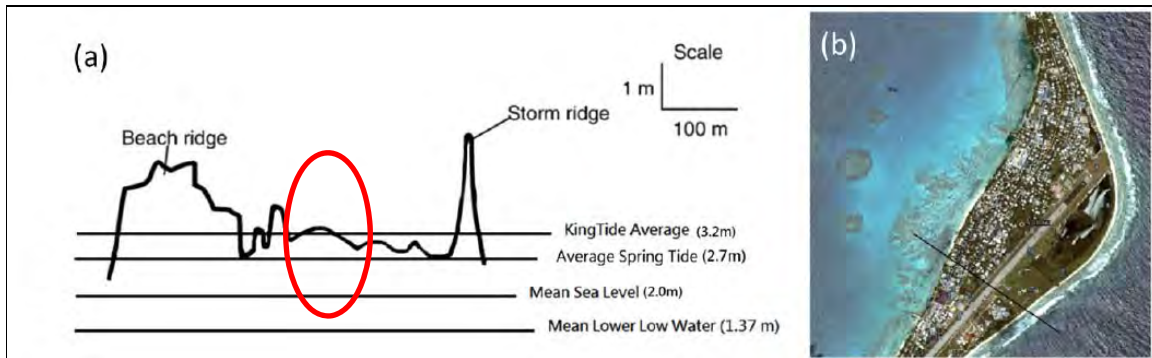


Figure 2.3: A Profile of Funafuti Indicating Tidal Levels and how it Relates to the Runway (Lin et al., 2014)

2.2 Mechanism of Short term Localised Water Level Rise due to rainfall

Taking more than 30,000,000 years in the making, atolls have their origins from Volcanic Islands that get eroded away by corals until a ring-shaped coral reef island remains (National Geographic, 2017). The remaining reef island is completely permeable with a fresh water lens below the island (Refer to Figure 2.4.) As expected, this freshwater lens will then move up and down with the tidal patterns of the ocean and swell up during rainfall events due to freshwater being less dense than salt water and hence “floating” on the tide. Taking into account the information found in Section 2.1, it is thus understandable that the top of the water lens is pushed up above ground level during spring tides and more so when heavy rainfall coincides with the tide event

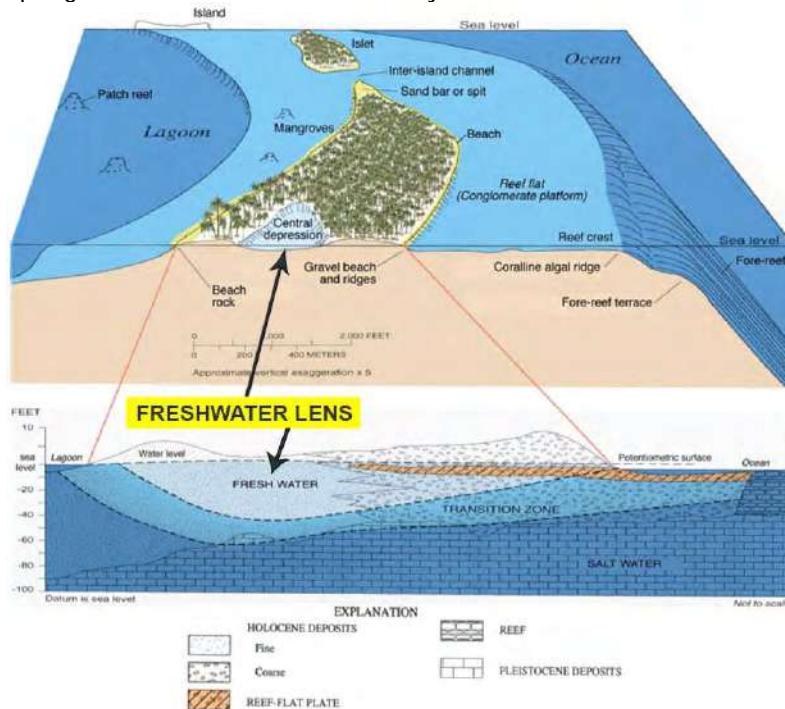
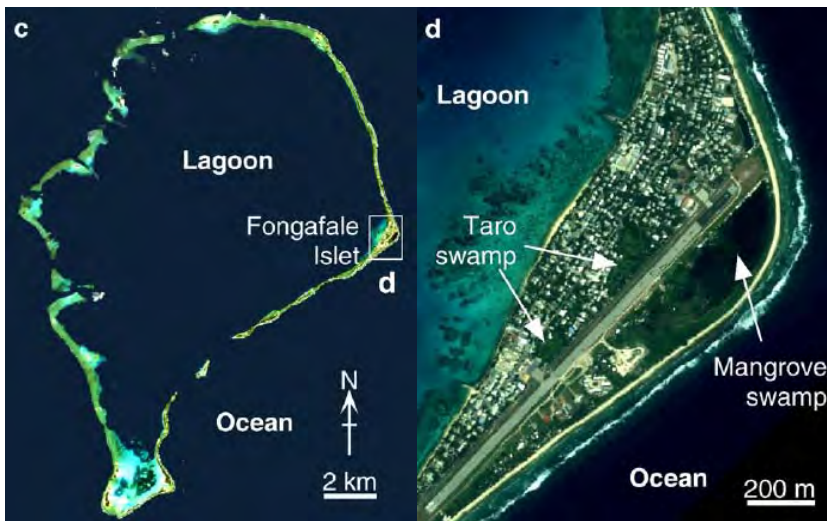


Figure 2.4: Fluctuation of Ground Water on Atoll Islands (Fletcher & Richmond, 2010)

2.3 Historical Context of the Funafuti Runway

The most significant challenge with building a runway on an atoll island is that a long, flat piece of land is required, something that is not often available on these low lying land masses. It is thus understandable that runways will be frequently constructed on reclaimed land from what was either part of the sea or swampy areas and/or in very close proximity to the coastline. This was exactly the situation when the Funafuti runway was built during the USA Force's Pacific campaign in 1943. Figure 2.5 present the contextual maps that show the original state of the island and where the runway was constructed. Through their work Yamano et al. (2007) were accurate with identifying the flood risk areas as these are exactly the location where current problems are experienced on the runway.



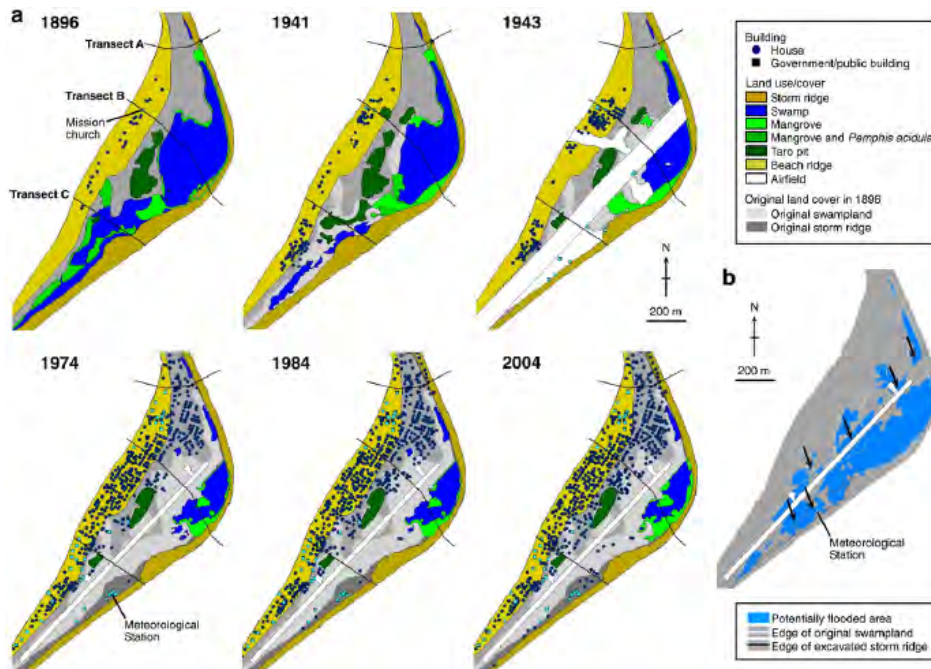


Figure 2.5: Contextual Maps for the Funafuti Runway Development (Yamano et al., 2007)

2.4 International Case Studies of Similar Issues on Runways and Coastal Infrastructure

The preceding sections have provided an insight into the origin and mechanism of the ground water rise issues experienced on the Funafuti runway. This section considers some case studies of similar problems experienced on runways constructed in similar situations and having similar rising water issues.

2.4.1 Hong Kong

Context

Leung et al. (2007) documented a useful case study of a similar issue that occurred on the new runway for the Hong Kong airport that opened during 1999. Some background to the construction includes:

- It was constructed on reclaimed land;
- A flexible pavement was designed with an Asphalt surface, crushed aggregate base course, and crushed aggregates sub-base; and,
- Soft marine clay, which blankets most of the seabed, was removed by dredging. This was followed by 2-4 meter thick marine sand capping layer overlaying 13 meters rock fill which in turn is underlain by 5-10 meters of marine sand to dredge level.

Observed Failures and Causes of Failure

Heaving of the runway surface was observed almost directly following the opening of the runway (some as high as 400 mm and a diameter of up to approximately 10m). The heaving was observed following prolonged rain spells. One year following the construction the heaving progressed into secondary defects such as delamination, cracking and potholes. Figure 2.6 illustrates some of the secondary defects.



Figure 2.6: Damage on the Hong Kong Runway (Leung et al., 2007)

Investigations yielded potential causes of the damage to include:

- *“vapourisation of moisture trapped beneath the wearing course as a result of high pavement temperature (more than 60°C) during sunny days, as experienced by some other airports. However, the heaving occurrence data on rainy days indicated that temperature was not a direct cause of the heaving;*
- *Based on the porosity of the sand capping layer and the rainfall data during the heaving incidents, the rise of water table did not exceed 0.5m. It was, therefore, unlikely that the heave was associated directly with water pressure lifting the wearing course, as the perched water table would remain well below the underside of the pavement. The rainfall acted as a trigger for the heave damage rather than being directly responsible (Note: this observations was different form the Tuvalu case);*
- *Review of the tidal record indicated that all of the heaving incidents occurred during a rapidly rising “Spring” tide and after continuous, heavy rainfall for a few days. Spring tides are associated with either a full moon or new moon and are the highest tides of the monthly cycle. A high tide is associated with a rapid rate of rising tide approximately 3 hours before the actual high tide. Site measurements revealed that the water level during a rising tide was almost 5 meters below the pavement surface, the heaving caused by direct tidal water force was also ruled out (Note: this observations was different form the Tuvalu case);*
- *After review of the combined tide and rainfall record, followed by site measurement and laboratory soil testing, the investigation concluded that the pavement heaving was caused by the build-up of air pressure underneath the pavement due to the rising tide and blockage of free air flow in the saturated capping sand layer. Under the dry weather, a*

rising tide would push the air in the void below the geotextile up through the relatively permeable sand capping, and this air would escape slowly through the pavement layers or the landscaped areas. (Figure 2.7) During periods of heavy rain, a perched water table built up within the sand capping layer directly above the geotextile and the soil in the landscape area was saturated with rainwater. The air permeability of the saturated soil was reduced.

- The wetting of the surface of the asphalt also reduced the air permeability of the asphalt pavement and its ability to dissipate air pressure. The rapidly rising tide pressurised the trapped air in the air voids in the granular layer beneath the pavement and caused the heaving.”

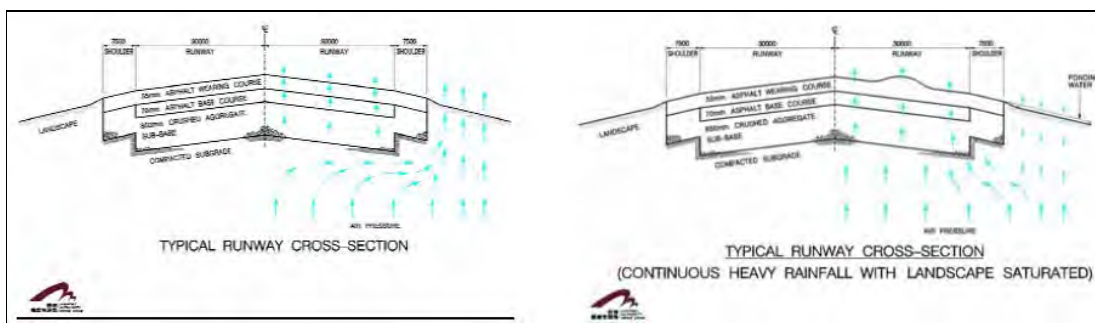


Figure 2.7: Illustration of Water and Vapour Movement through the Pavement (Leung et al., 2007)

Vapour monitoring was also installed to understand the mechanism better.

Remedial Actions

The remedial work was undertaken in two stages:

- A short-term measure included maintenance staff inspecting the surface of the runway following heavy rainfall and drilling holes into the surface using an electric hand-drill. A total of 160,000 holes were drilled to relieve the immediate pressure under the asphalt. Subsequently, a Ground Penetrating Radar (GPR) survey was undertaken to isolate areas where the asphalt surface was delaminating from the base course;
- For the long-term solution, several options were considered including:
 - Permanently retaining the pressure relief holes through the asphalt pavement.
 - Installing extensive cut-off barriers to eliminate tidal movement in the fill.
 - Overlaying the pavement to increase thickness and weight to resist the uplift air pressure.
 - Anchoring the asphalt surfacing down to the underlying subgrade to prevent the formation of domes.
 - Introducing a vent system to release the air pressure. (e.g. vent pipe down to the rock fill; side vent trenches along pavement edges)

The success of the venting system has been monitored through a permanently installed on-line pressure monitoring system. On establishing a successful outcome, the temporary drilled holes were sealed to prevent further damage to the surface via water ingress from above.

2.4.2 Albany City Airport & Barrow Island - Australia

Context

Little information was available from the construction details of the runway on the Albany City Airport and the runway at Barrow Island. The Albany City runway was sealed with a double chip seal consisting of cut-back bitumen with 10mm and 7mm aggregate cover. The runway at Barrow Island also had a double coat chip seal with similar specifications to that of the Albany City Airport.

Observed Failures

From the evidence provided it was noted that the seal was constructed to provide a water-tight surface. In the presence of rising ground water, there was a build-up of vapour pressure that lifted the seal up to form blister patterns similar to that of the Funafuti runway (Refer to Figure 2.10). The same defects were also observed on the Barrow Island runway, but it was a limited occurrence following a cyclone event². A fundamental difference between these two runways and Funafuti was that both the Australian are inland airfields (no tidal effects) and the blistering issue has only occurred following significant rainfall events. Also, the only defect observed was the blistering with no other secondary defects.



Figure 2.10: Blistering on the Seal at Albany City Airport (Paul G Robertson & Associates, 2011))

Note: The same large seal "blister" after the seal surface had been broken and lifted with the adjacent shovel to release any gas or vapour. The gravel pavement surface was dry before the seal was opened.

Remedial Actions

The blistering issue at Barrow Island was resolved by overlaying the runway with a 50mm asphalt surface. The runway at Albany City was repaired by using a screwdriver to puncture the surface to

² Personal discussion with Fraser Sparks Aerodrome Management Services Pty Ltd

let the vapour escape, leaving the surface to dry out and then rolling the surfacing using a pneumatic multi-tire roller.

2.4.3 A Scan of International Guidelines

International guidelines for chip seals and airport runways were scanned, and currently, the type of blistering failures observed in Tuvalu is not covered in any of the guidelines. It is recommended that the treatment of ground water rise from below pavement surfaces should be documented in relevant publications.

3. Methodology

3.1 Scope of Work

The scope of works included:

- Mobilisation of two field technicians from Geotechnics Ltd and associated field equipment;
- Excavation of two test pits alongside the runway to install two standpipe piezometers.
- Installation of levelloggers within the piezometers;
- Coring of four shallow pits through the runway pavement to a depth of 0.2m;
- Installation of vapour pressure transducers within the pavement pits and associated cabling to a flush toby box at the side of the runway;
- Installation of a barologger on site to record barometric pressure.
- Collation of the testing data and monitoring results; and

3.2 Field Installations

Two field technicians from Geotechnics Ltd undertook the site investigations and instrumentation installation between 3- 7 March 2017. A representative of Auckland Uniservices, Dr Theuns Henning, was also present during the investigations. The work included:

- Excavation of two test pits adjacent to the side of the runway to a depth of 1.4m
- Installation of a single 32mm dia. PVC standpipe within each pit (BH1-2) to a depth of 1.4m bgl.
- Installation of levelloggers within the PVC Standpipes to monitor groundwater levels.
- Coring four additional test excavations through the airport runway and taxi apron to a depth of 0.2m.
- Installation of a vapour pressure logger within each cored hole with a direct read cable to read the information outside the runway apron to record vapour pressures under the airport pavement.
- Reinstatement of the runway pavement with rapid set, high strength grout and sealant.
- Installation of a barrologger within the airport compound to record barometric pressure at the site.



Figure 3.1: -Installation of Piezometer in BH1 and Installation of vapour pressure logger within the shallow pit.

The two levelloggers were installed adjacent to the runway in the locations shown below. Refer to the site plan in Appendix A for the installation locations.

The ground conditions are summarised on the attached site investigation summary in Appendix B. Levellogger 1 was installed on the side of the runway adjacent to the terminal. Levellogger 2 is located on the opposite side of the runway, opposite the Ministry of Works building.



Figure 4-Levellogger installations near the terminal building (6 March 2017)

Table 3.1 summarises the records for the levellogger installations.

Table 3.1 Levellogger installation summary

Description	Levellogger	
	1	2
Surface Elevation RL (m) – Funafuti Local Datum	3.3	3.2
Total depth BGL (m)	1.4	1.4
Actual Installation depth (m)	1.2	1.2
Monitoring period starts	4/03/2017 14:00	4/03/2017 13:30
Monitoring period ends	7/03/2017 06:15	7/03/2017 06:00
Range of water level BGL during monitoring period (m)	0.58-1.03	0.13 - 0.92

Vapour pressure loggers BH1A-B and BH2A-B were all installed at a depth of 0.2m below the runway pavement and subsequently backfilled. These have been set up to continuously monitor from the 6th of March 2017. The barrologger was installed within the desalination plant adjacent to the site and was mounted on 6th of March 2017. Compensated data is therefore only available from 6 March 2017 as displayed in the appended charts. Technical specifications of the levelloggers are provided in Appendix G.

3.3 Subsurface conditions

3.3.1 Pavement condition – March 2017

On the runway, a few new minor depressions/ venting areas were found during the fieldwork that will require patching in the future. The current patches are performing well as no visible distress was observed during the visit. We note no spring tides occurred in this period. The pavement materials typically comprise 20mm thick chip seal cover overlying a 90mm thick basecourse layer comprising 20mm-120mm diameter weathered crushed coral aggregate with some silt.

3.3.2 Subgrade condition

The subgrade material typically comprises 100mm-300mm coral fragments with some fine to coarse sand infill material. This material was tightly packed and white in colour.

3.3.3 Coral Rock

The basal unit encountered in the investigations was in-situ coral rock. This unit was encountered at a depth of 1.4m across the site. The excavator bucket was unable to penetrate this formation.

3.3.4 Groundwater

Groundwater was found to be at approximately 0.8m below ground level during the excavation for the groundwater monitoring instrument/installation. Observations during the visit confirmed that the groundwater at the site is tidally influenced and daily variations in groundwater levels were noted. The levelogger installed within BH2 appeared to display a one hour delay with the observed tidal variations. The locations of the instrumentation are provided in Appendix A.

4. Results

4.1 Pre-design and As-built Information

The recent upgrade project for the Funafuti airport included the following treatments:

- Treatments to address runway surface depressions and stabilise the existing surfacing;
- Construction of new runway end turning bays;
- Installation of ducting across the central runway section for future AGL and related cabling works;
- Extending the apron area pavements;
- Partial reconstruction of the taxiway formation to address pavement strength and surface flooding issues;
- Installation of two soakage pits adjacent to the taxiway in the grass berms to reduce ponding –surface flooding;
- Resurfacing of the main runway, taxiway and apron areas;
- Jet seal treatment over the localised apron parking area;
- New runway and taxiway paint markings (noting that apron markings are deferred until the terminal building works are completed and the final parking position can then be used).

4.2 Visual Observations

A number of post-construction inspections were completed by AECOM, the World Bank and this project team. The visual observations were consistent in noticing the following:

- The blistering mechanisms only occur during spring tides, especially when these coincide with rainfall storms (Refer to Figure 4.1);
- During the blistering the surface completely dislodges from the base course and even dislodges the upper part of the base course;
- Where blistering has occurred, permanent delamination damage often occurs in the basecourse surface leading to depressions on the surface of the runway (Figure 4.1);
- Given the natural formation of coral atolls, they are expected to have natural venting paths within the sub-grade structure (Figure 4.3). The photo shows the white areas of dried salt where coronous rock is exposed at the surface;
- There are venting holes that have developed in certain areas of the runway, these vents seem to be effective in alleviating the pressure below the runway surface; and,
- The pothole patches that have been constructed through the Funafuti Works Department seem to be effective in addressing the defects. There is, however, evidence of new venting issues developing within the same vicinity of the patches signalling an on-going issue.

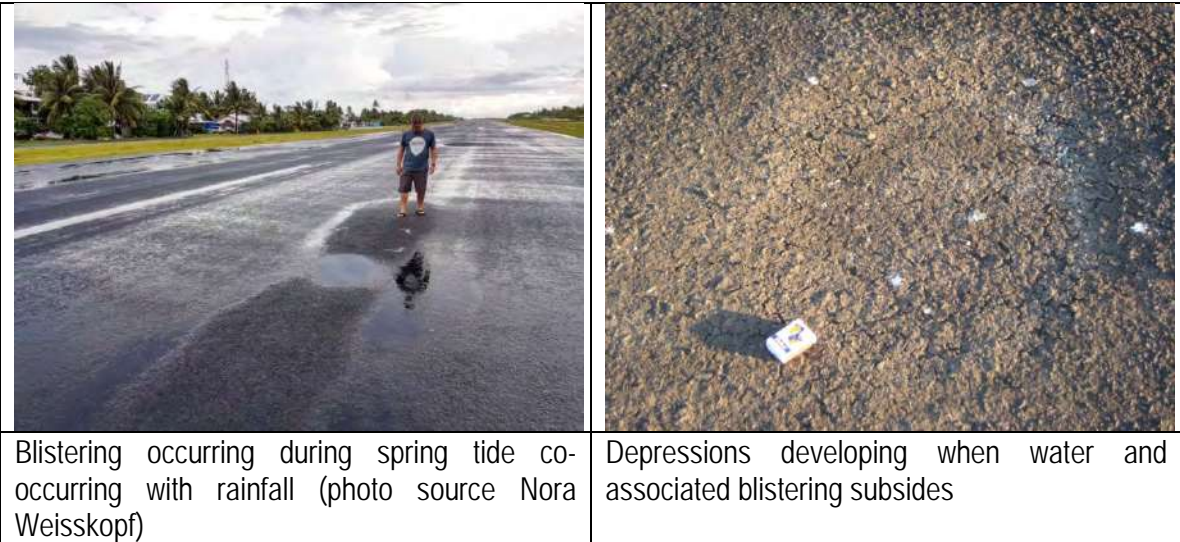


Figure 4.1 Blistering Mechanism on the Funafuti Runway



Figure 4.2: Surface Venting Holes and Patching of the Runway



Figure 4.3: Evidence of Venting Paths Through coral sub-grade Formation (Source Glenn Fawcett)

The visual inspections concluded that there is an on-going issue and need to vent the pressure build-up beneath the runway surface. Attempts to seal this off would be futile as the entire substructure is pervious and water levels are rising above surface level thus resulting in an inevitable pressure build-up. Remedial options need to include some degree of sub-surface venting.

4.3 Sea Level Measurements

The water level logger at Site 1 recorded water level fluctuations which mimic the tidal fluctuations albeit on an attenuated basis. The tidal fluctuations generally range from 0.7m to 2.1m on an about fortnightly cycle whereas the water level range varied between 0.2m and 1.1m (refer to Figure 4.4). The high rainfall event at the beginning of April caused a 0.3 m rise in the groundwater level which was superimposed on the tidal fluctuation resulting in the water level reaching ground surface over the period of April 3rd and 4th.

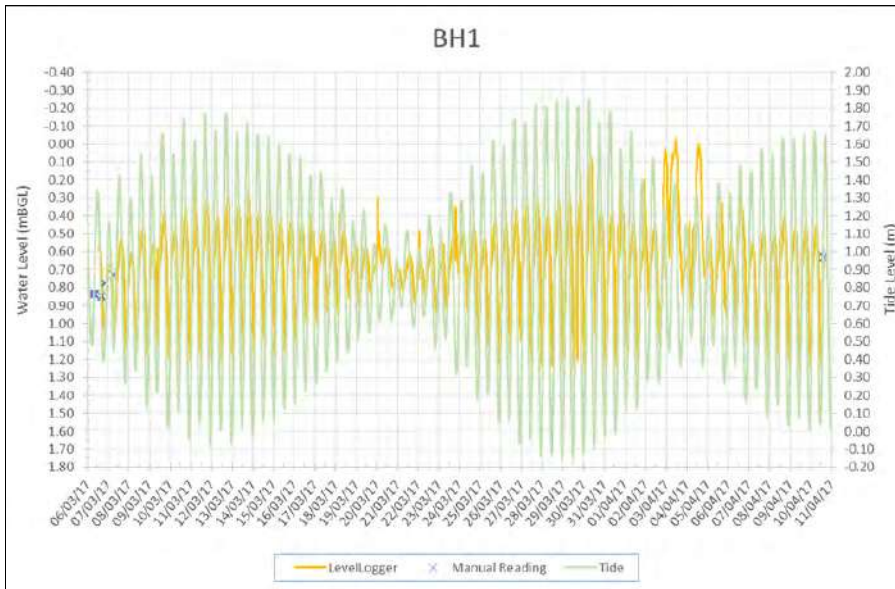


Figure 4.4: Water Table and Tidal Level Measurements (Levellogger Site 1)

During the time of this report, insufficient data was received from the second borehole, with the levellogger being replaced on 14th April. However, it is expected to observe better correlation with the tidal fluctuations from this borehole. Figure 4.5 illustrates the difference in water table from the two boreholes during the manual measurements on site during the initial installation. Better potential correlation with the tidal fluctuations is evident for the levellogger at site 2.

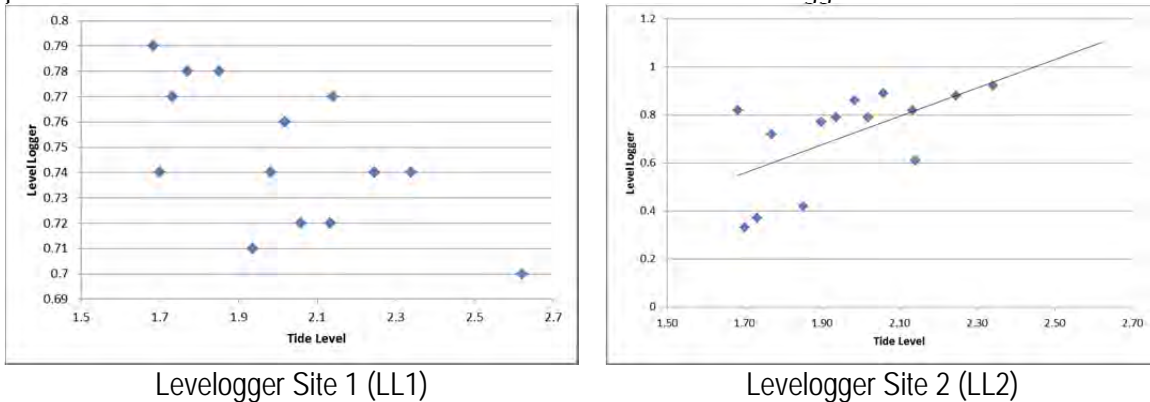
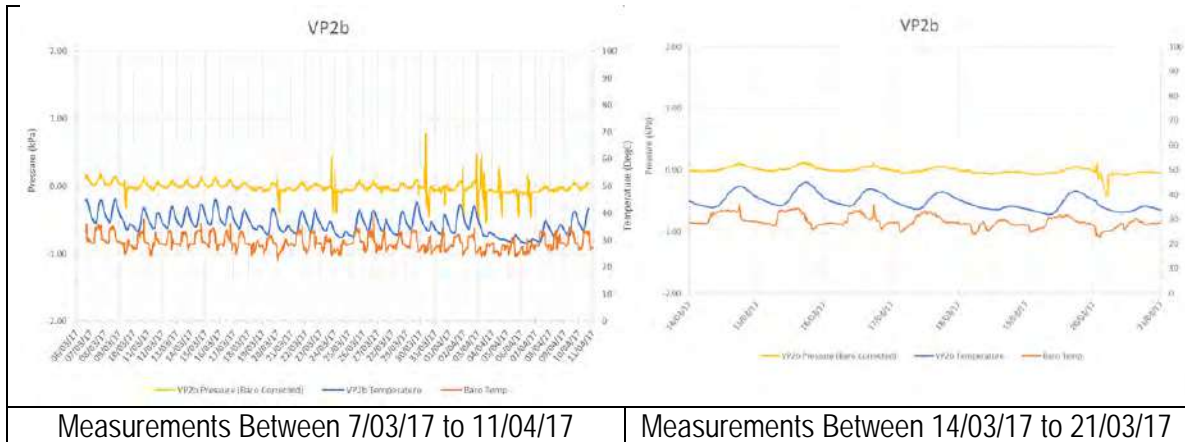


Figure 4.5 Comparing Manual Readings Water Level from the two Boreholes

4.4 Vapour Pressure

The recorded pressures at each of the four gauge locations show a very similar response. Figure 4.6 and 4.7 give some examples of vapour measurements at Site 2b. The full record of the results is provided in Appendix C. The pressure fluctuates by approximately 0.5 kPa on a 12-hourly cycle but there is a smaller fluctuation of approximately 0.1 kPa which occurs midway between the larger fluctuations. These fluctuations mimic the tidal fluctuations but are much attenuated.

Superimposed on these short-term cycles there appears to be a longer term cycle which repeats approximately monthly (during spring tides) with an amplitude of 0.6 kPa.



Measurements Between 7/03/17 to 11/04/17 Measurements Between 14/03/17 to 21/03/17
 Figure 4.6: Comparing Vapour Pressure with Temperature Measurements at Vapour Site 2b

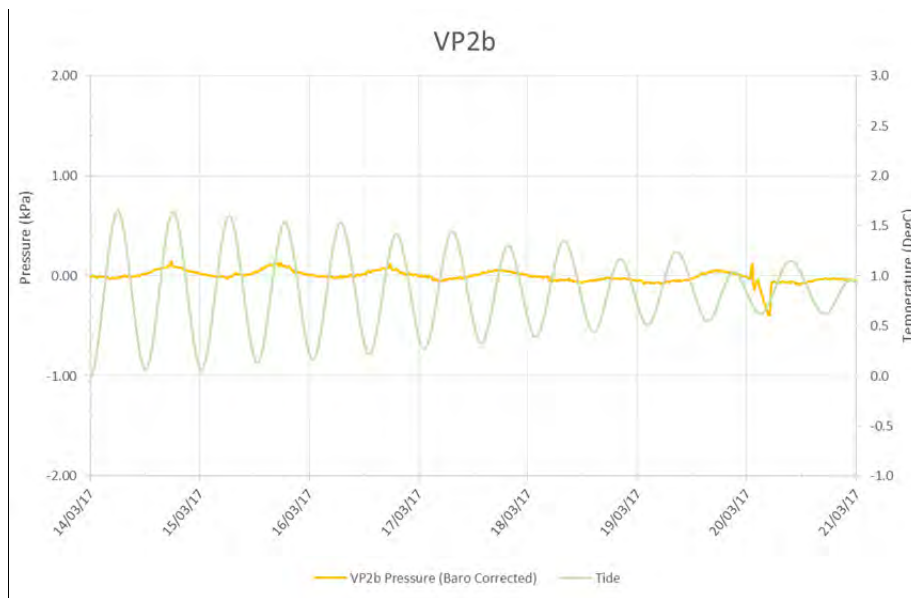


Figure 4.7: Comparing Vapour Pressure Measurements with Tidal Fluctuations (Site 2b)

When the gauge pressure is corrected for the prevailing atmospheric pressure, the longer term cycle disappears which would indicate that the vapour pressure merely reflects variation in the atmospheric pressure. A longer term record may indicate the repeatability of this cycle. The corrected pressure records also show that gauge pressure does not exceed atmospheric pressure by more than 0.2 kPa except for "spikes" which appear on a random pattern.

These peaks/"spikes" in pressure are more noticeable both in their frequency and amplitude at Site 1 than Site 2 for reasons that are not clear. In some instances the spikes" coincide with heavy rainfall events (e.g. the 170 mm of rain which fell on April 2nd) while others appear to coincide with

increased fluctuations in the temperature but it is not clear whether these are causally linked or both causally linked to some other common factor. The amplitude of the spike in some cases is represented by an almost equal rise and fall in the corrected pressure but in other cases it is predominantly a rise in pressure. The next section investigated the peak occurrences in more detail.

4.5 Statistical Analyses

Additional statistical analyses were undertaken with the aim of isolating the occurrence of pressure peaks/ "spikes" observed from the field measurements. The peak values used for both the water table and pressure measurements were:

- Peak Water Levels:
 - BH 1 < 0.3m
 - BH 2 < 0.5 m

- Pressure peaks (barro corrected):
 - VP1 a and b > 0.8 KPa
 - VP2 a and b > 0.4 KPa

Note that the specific ranges were visually selected in order to minimise the number of peak values for the prevailing conditions for each test location. It is expected that measurements from different test locations would differ for a number of factors including installation conditions, accuracy of instruments and a physical difference in the measured parameters.

Table 4.1 present the outcome from the field instrumentation. Each column provides the ratio of positive versus negative outcome for the postulated correlation factor. The 90th percentile significance indicates the repeatability between the paired measurements (i.e. agreement between two level loggers and agreement between two vapour instruments within a similar location).

Observations from the table are:

- The measurement ratios between the two level loggers are within a 90th percentile confidence level while the pressure measurement did not yield the same consistency in measurements. Given the multiple factors that influence on the subsurface pressure this outcome is not completely unexpected;
- There is a definite correlation in the occurrence of peaks in water level and pressure levels with high tides. Obviously the correlation between the measured water table and consequential pressure peaks are the strongest; and,
- There is a correlation in water table peaks and the coinciding tidal and rainfall occurrence, whereas the same correlation does not exist with peaks in the measured vapour pressure.

Table 4.1: Investigating the Occurrence of Peak Measurements

Potential Correlation Factor	LL1	VP1a	VP1b	LL2	VP2a	VP2b	Significance p<0.1?
Peaks in water level measured as a function of tidal peaks alone	✓ 134:1 7	N	N	✓ 71:1	N	N	0.01
Peaks in water level measured as a function of rain storms alone	✓ 90:39	N	N	✗ 22:38	N	N	0
Peaks in water level measured as a function of tidal peaks combined with rain storm	✓ 90:60	N	N	✓ 40:32	N	N	0.08
Vapour pressure peaks as a function of water level measured	N	✓ 49:2	✓ 16:1	N	✓ 5:0	✓ 5:0	0.36 0
Vapour pressure peaks as a function of tidal peaks alone	N	✓ 32:19	✓ 12:5	N	✓ 7:3	? 3:2	0.27 0.35
Vapour pressure peaks as a function of rain storms alone	N	✗ 21:26	✗ 7:6	N	✗ 5:5	✗ 2:3	0.28 0.35
Vapour pressure peaks as a function of tidal peaks combined with rain storm	N	✗ 21:30	✓ 11:6	N	✗ 3:7	✗ 1:4	0.03 0.35

Legend:

- ✓ Conclusively Positive
- ✗ - Conclusive Negative
- ? – Inconclusive Result
- N- Not relevant
- Values – positive:negative

4.6 Discussion

Vapour pressures beneath the runway are generally likely to be at or below atmospheric pressure which would not explain the blistering given that the dead weight of the surfacing is approximately 0.5 kPa and there would be further resistance provided by the bond strength between the surfacing and the base course. However, the intermittent spikes in pressure would be sufficient to lift the surfacing even allowing for the bond between the surfacing and the base course.

The logical extension of this conclusion is that there would be more pronounced blistering in the vicinity of Site 1, where the pressure spikes have been greater and more frequent, than Site 2 but this is not borne out by the observations. The only further explanation is that the strength of bond between the surfacing and the basecourse at Site 1 has compensated for the pressure spikes.

The mechanism causing the pressure peals have been investigated and presented in Section 4.5. There is statistical significant evidence that the pressure peaks coincide with high tides (Spring

Tides and or Kind Tides) and some indications that it may be further elevated with coinciding rainstorms. The collected data details level did not allow for a statistical significant confirmation of the combined impact of high tides and rain storms.

Despite not fully understanding the mechanism the solution would either be a pressure relief system similar to that used in Hong Kong or at least a 60 mm thick asphalt overlay similar to that adopted at Barrow Island. However, as an interim measure, the solution adopted at Albany and which was also adopted for a similar blistering problem on Norfolk Island in the 1980s was trialled and it has proven to be a successful interim solution (Refer to memorandum on subsequent tests in Appendix D).

5. Recommendations for Addressing Tidal Influence and Rapidly Fluctuating Ground Water Levels

5.1 Options for Remedial Work

On the basis of evidence collated in this study, there are some fundamental principles that underpin the remedial work requirements and future design of vertical infrastructure that are subjected to high tidal levels. There are:

- Given the formation of a coral atoll, **the subgrade will always be highly permeable**. It can also be assumed that the natural aggregate pavement layers would also be permeable, especially if the material is also of coral origin. Therefore the end product is a permeable structure that will allow water table movement to raise up to and through the pavement surfacing. For this reason, grouting of existing drainage paths is not advisable; and,
- Under these circumstances, **having a water-tight surface layer simply does not work**. The combination of a fast rising tide results in increasing water and vapour pressure below the surface. These pressures are sufficient to lift even thick asphalt surfaces such as has been the case for the Hong Kong airport. In situations where a strong bonding exist between the surface and the pavement layer, subsequent base course failure will be a secondary defect to the blistering process; and,
- **A mechanism has to be provided to relieve the pressure** from below the surface. This mechanism also has to be supplemented with sufficient subsurface side drains that will remove the water away from the pavement promptly.

Some potential remedial options for Funafuti runway's surface blistering issues are summarised in Table 5.1.

Table 5.1: Remedial Options for Funafuti

Option	Description	Cost Estimate (Million)
Base Line – not to resurface	It is not recommended to consider a re-surface at this point before drainage aspects have been constructed. There is a significant risk of water still penetrating through the current surface layer. Delamination of the new surface would be unavoidable.	Included to options below
Base Line – Cut-off Drains	Install cut-off drains on both sides of the runway in location where failures are occurring	Included to options below
Short Term Option	Install vertical venting drains as part of the patching strategy to prevent the formation of new venting paths. A similar design to that of the Hong Kong case study is recommended	\$1,767
Medium-term Option	Install herringbone subsurface drainage in affected/high-risk areas. If possible, horizontal drilling should be considered as a cost-effective option. A priority drainage zone would include at least 1/3 of the length of the runway and include 2/3 of the	\$7,837

Option	Description	Cost Estimate (Million)
	width of the runway (1/3 on both sides)	
Long-term option	Install herringbone subsurface drainage using a trenching method and reconstruct base course. This option has to consider a more permeable surfacing option.	\$8,612

It is further recommended maintaining the monitoring of the water table rising impact on the runway through further installed piezometer and vapour pressure, loggers.

The preferred option would be to install sub-surface fish bone type drainage system using a directional drilling technique. That way the current base course and surface does not have to be replaced. However, the final option will depend on engineering assessment of the integrity of the current base course.

5.2 Implications for Future Infrastructure Projects and Further Research

This study has highlighted the lack of publications and guidelines that cover the impact of rising sea levels or increasing tidal movements on coastal infrastructure. It is therefore recommended to:

- a) Widely publicise the outcome of this study in official bank publications and to a wider audience;
- b) Include recommended monitoring regimes of fluctuating water tables and vapour pressure monitoring as a standard pre-design data collection item to the Terms of Reference for future projects.

Lastly, there is a further research potential for developing low-cost permeable surface options for situations where it is unavoidable to construct pavement structure in fluctuating water-table conditions.

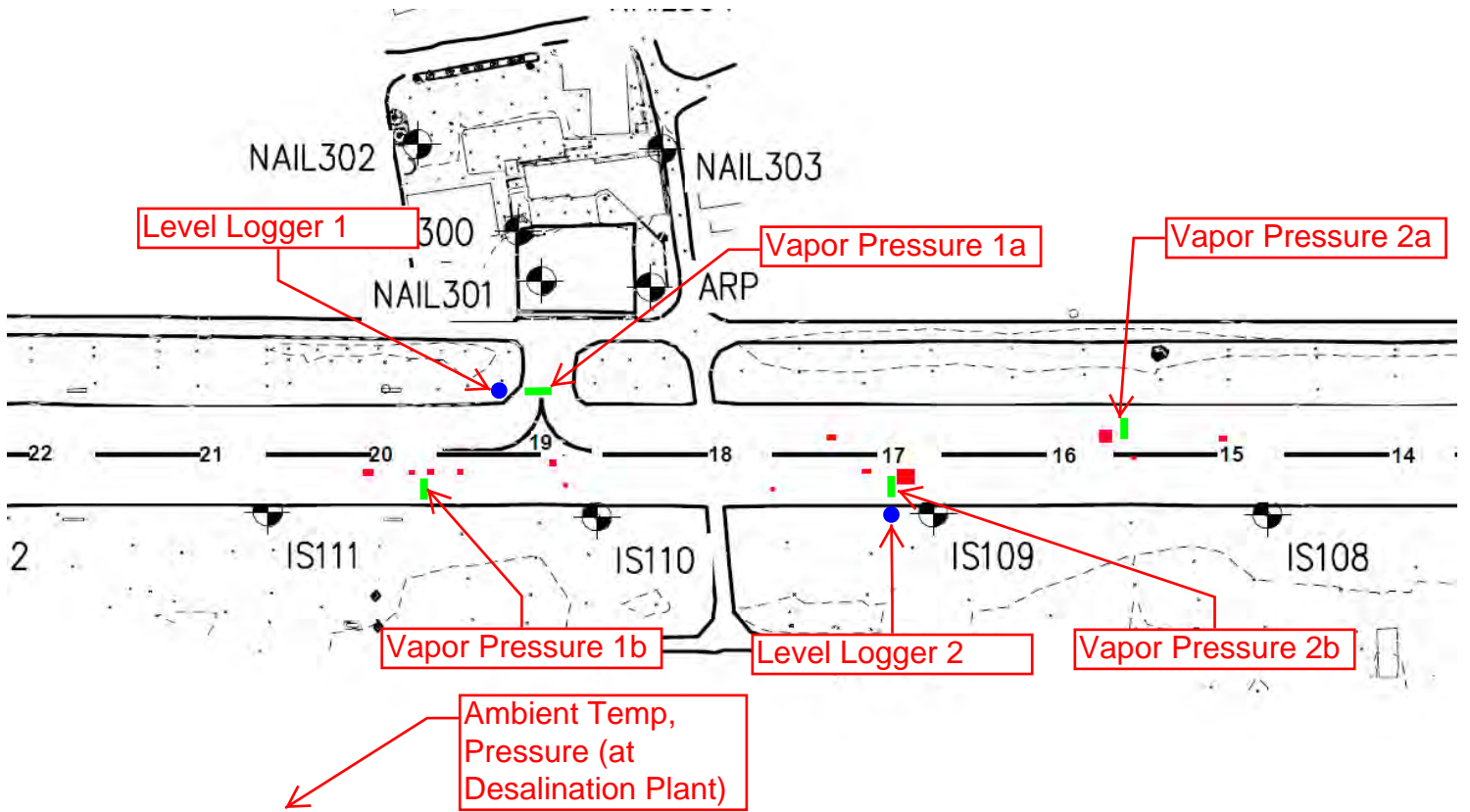
Recommendations for further monitoring also include:

- Continuous rainfall measurements should be undertaken on the island; and,
- The implemented options should be monitored for their effectiveness in addressing the issues. Therefore, further barometer installations should be included to any construction option applied.

6. References

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Appendix A: Site Instrumentation Plan



Appendix B : Test pit logs

EXCAVATION LOG

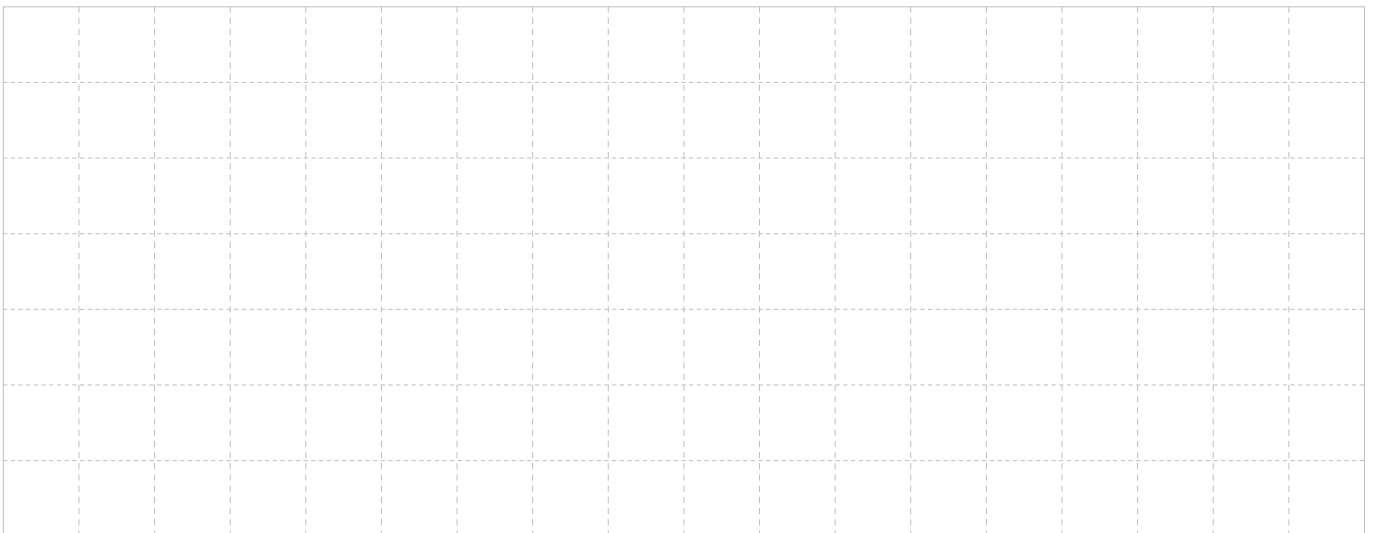
Excavation Id.: **BH2**

SHEET: 1 OF 1

PROJECT: Funafuti Airport	LOCATION: Funafuti Airport, Tuvalu	JOB No.: 1001315
CO-ORDINATES:	EXPOSURE METHOD: TP	EXCAV. STARTED: 06/03/2017
R.L.: 3.20m	EQUIPMENT: Backhoe Excavator	EXCAV. FINISHED: 06/03/2017
DATUM:	OPERATOR:	LOGGED BY: PZJ
	DIMENSIONS:	CHECKED BY: JWY

EXCAVATION TESTS			ENGINEERING DESCRIPTION				GEOLOGICAL					
PENETRATION	SUPPORT	WATER	SAMPLES, TESTS	SAMPLES	DEPTH (m)	SOIL NAME, PLASTICITY OR PARTICLE SIZE CHARACTERISTICS, COLOUR, SECONDARY AND MINOR COMPONENTS	MOISTURE CONDITION	WEATHERING	STRENGTH/DENSITY CLASSIFICATION	ESTIMATED SHEAR STRENGTH (kPa)	DEFECTS, STRUCTURE, COMMENTS	UNIT
1 2 3										10 25 50 100 200		
					3	20mm Thick asphalt Chipseal Bascourse 45/60mm GRAVELS, minor silt, dark brown; Tightly packed, moist.	M		D MD			Fill
		06/03/2017			0.5	COBBLES and coarse GRAVEL, minor fine sand and silt; White. Tightly packed, moist-wet.	M-W		MD-D			
					2							
					1.5	Coral Rock-Unable to penetrate with digger bucket	W / SW		VD			LimCR

SKETCH / PHOTO:



COMMENTS:

Hole Depth
1.4m

Scale 1:17

EXCAVATION LOG

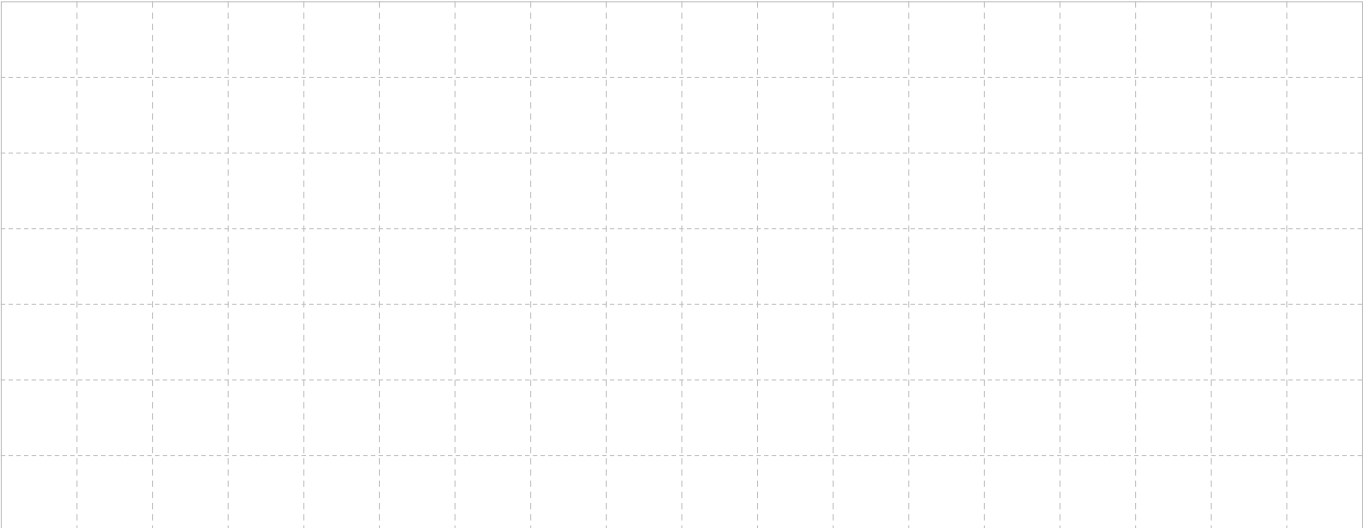
Excavation Id.: **BH1**

SHEET: 1 OF 1

PROJECT: Funafuti Airport	LOCATION: Funafuti Airport, Tuvalu	JOB No.: 1001315
CO-ORDINATES:	EXPOSURE METHOD: TP	EXCAV. STARTED: 04/03/2017
R.L.: 3.30m	EQUIPMENT: Backhoe Excavator	EXCAV. FINISHED: 04/03/2017
DATUM:	OPERATOR:	LOGGED BY: PZJ
	DIMENSIONS:	CHECKED BY: JWY

EXCAVATION TESTS			ENGINEERING DESCRIPTION				GEOLOGICAL							
PENETRATION	SUPPORT	WATER	SAMPLES, TESTS	SAMPLES	RL (m)	DEPTH (m)	GRAPHIC LOG	SOIL NAME, PLASTICITY OR PARTICLE SIZE CHARACTERISTICS, COLOUR, SECONDARY AND MINOR COMPONENTS	MOISTURE CONDITION	WEATHERING	STRENGTH/DENSITY CLASSIFICATION	ESTIMATED SHEAR STRENGTH (kPa)	DEFECTS, STRUCTURE, COMMENTS	UNIT
1 2 3												10 25 50 100 200		
								20mm Thick asphalt Chipseal	M		MD-D			Q1n
		04/03/2017; Tidally influenced				3		Bascourse 45/60mm GRAVELS, minor silt, dark brown; Tightly packed, moist.						Fill
						0.5		Coarse Coral GRAVELS and COBBLES, minor fine sand and silt; white. Tightly packed, well graded, moist to wet.	M-W		MD			
						0.75m		Becomes wet						
						2								LumpR
						1.5		Coral Rock-Unable to penetrate with digger bucket	M/SW		VD			

SKETCH / PHOTO:

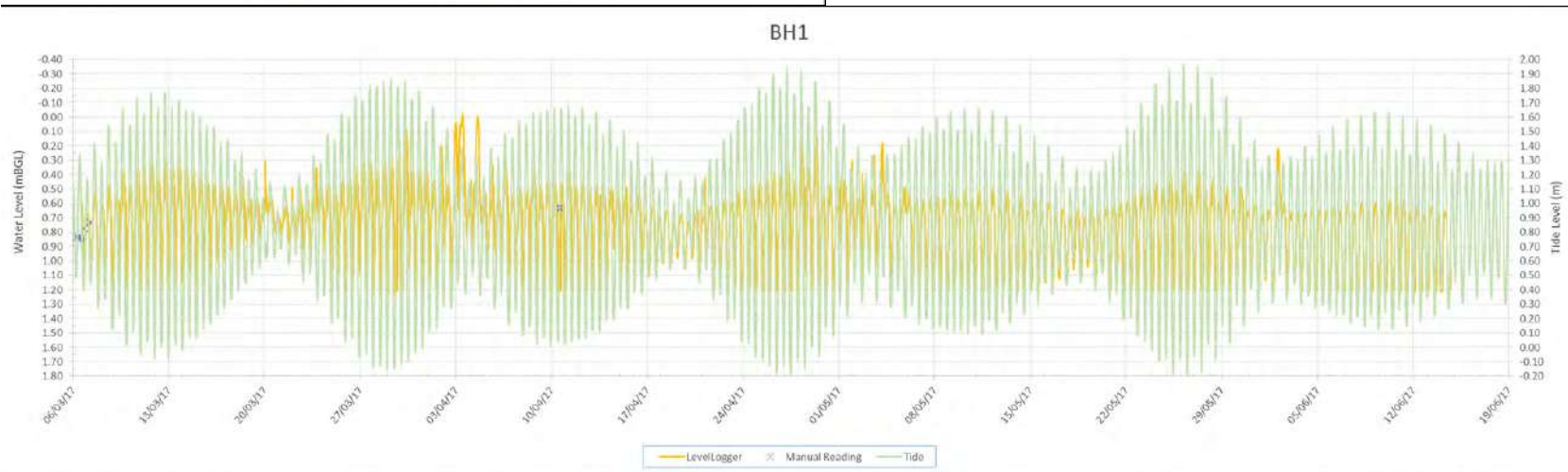
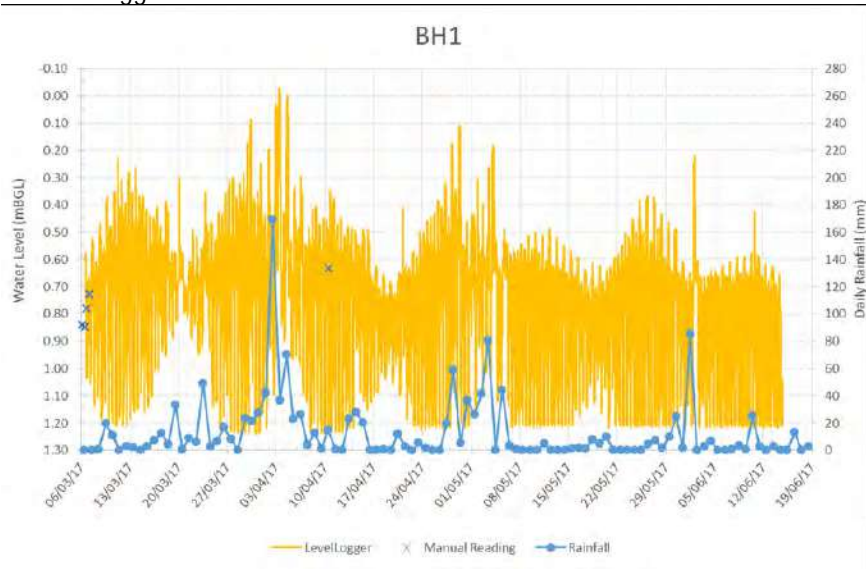


COMMENTS:

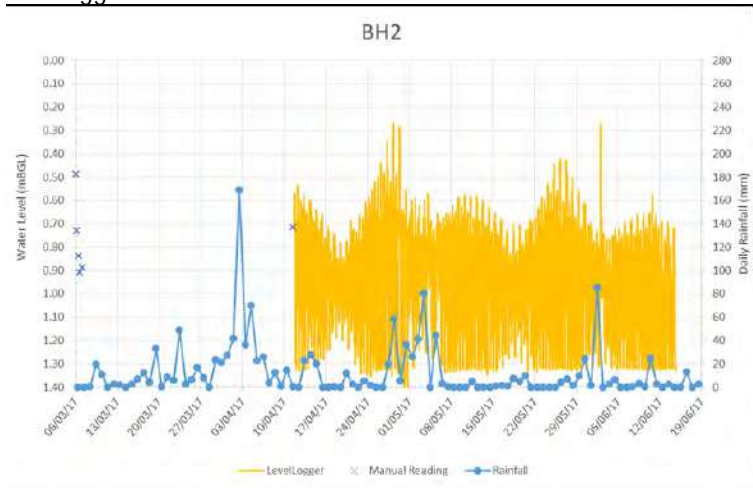
Hole Depth 1.45m

Scale 1:17

Appendix C : Groundwater and Vapour Monitoring Graphs
 Levellogger 1:

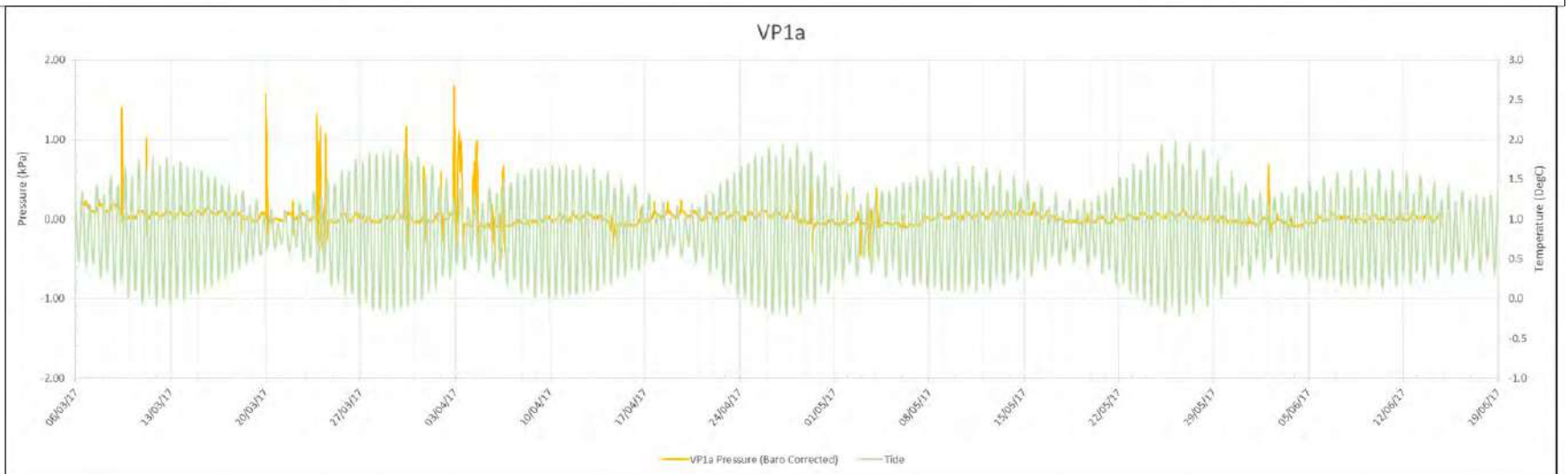
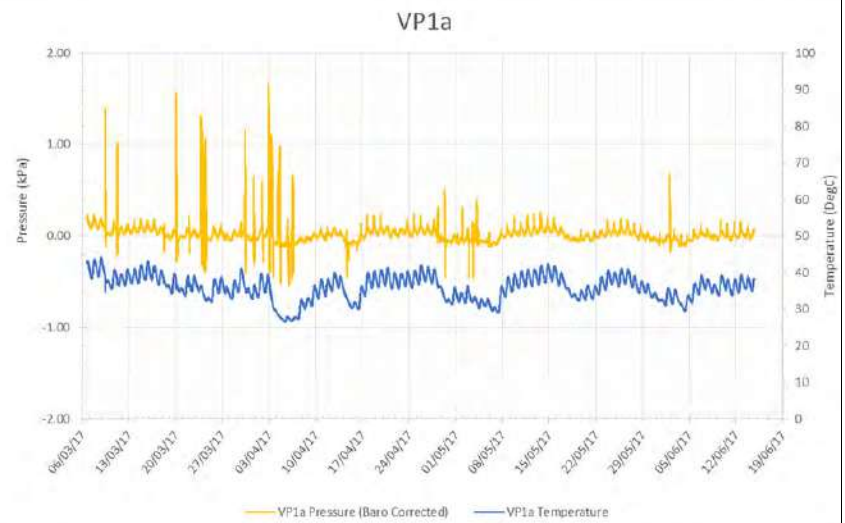
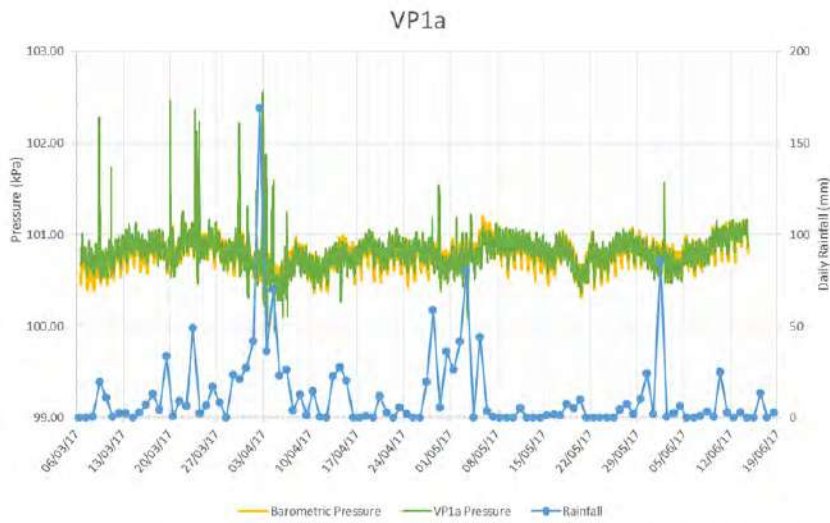


Levellogger 2:

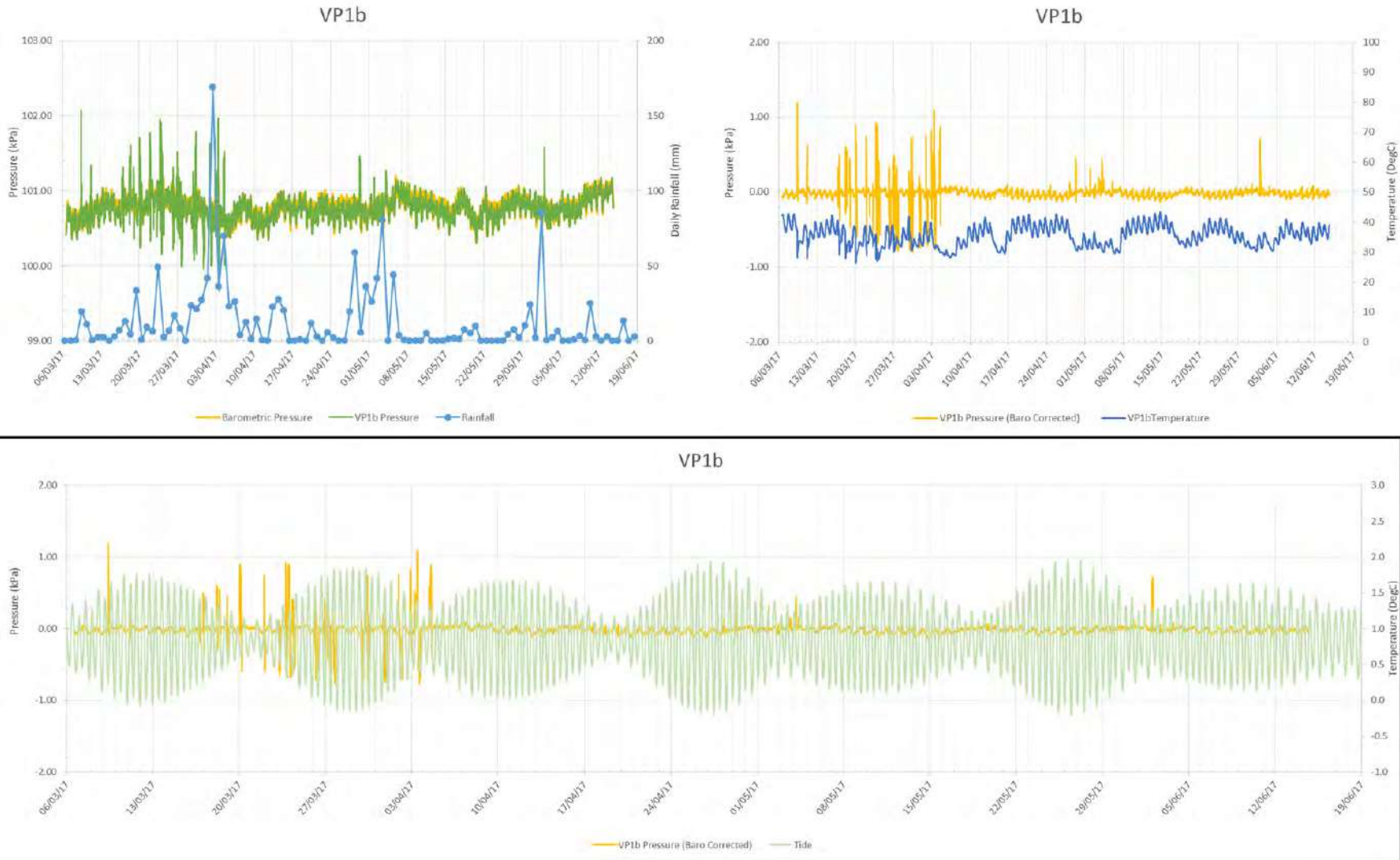


Note: Instrument malfunctioned during the first month

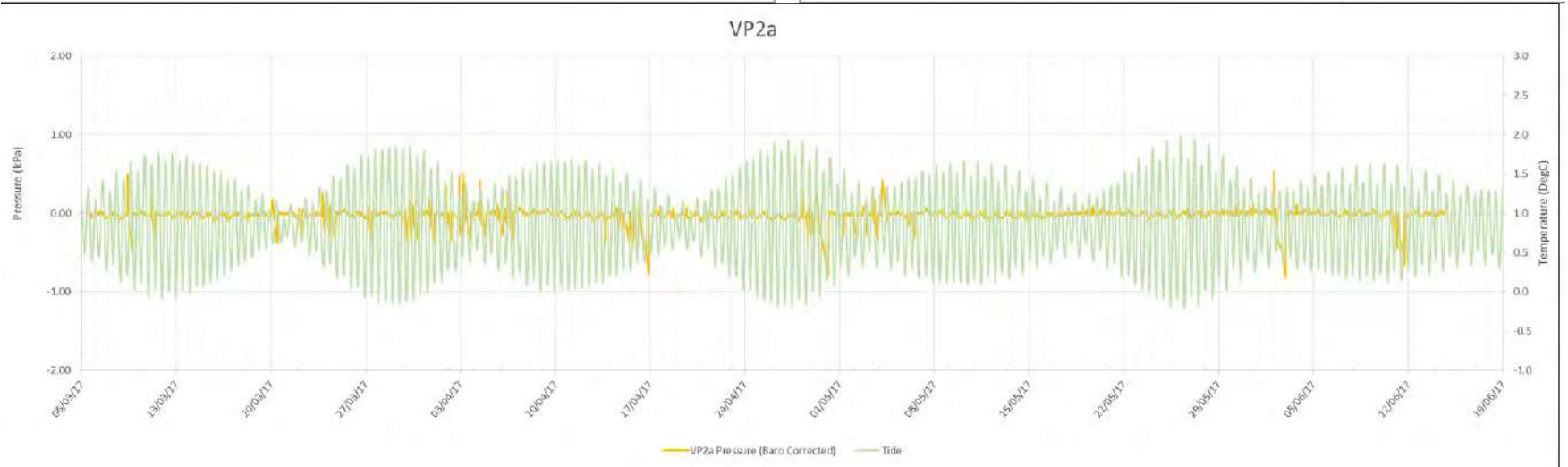
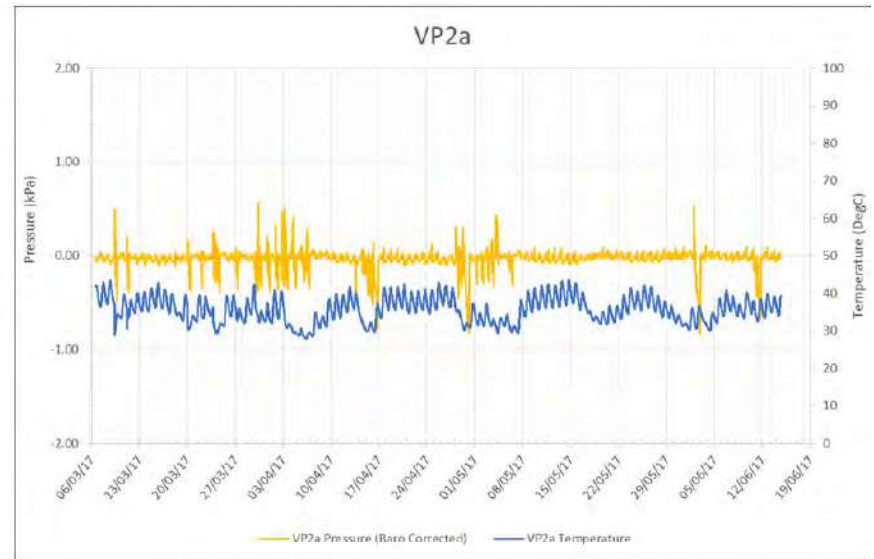
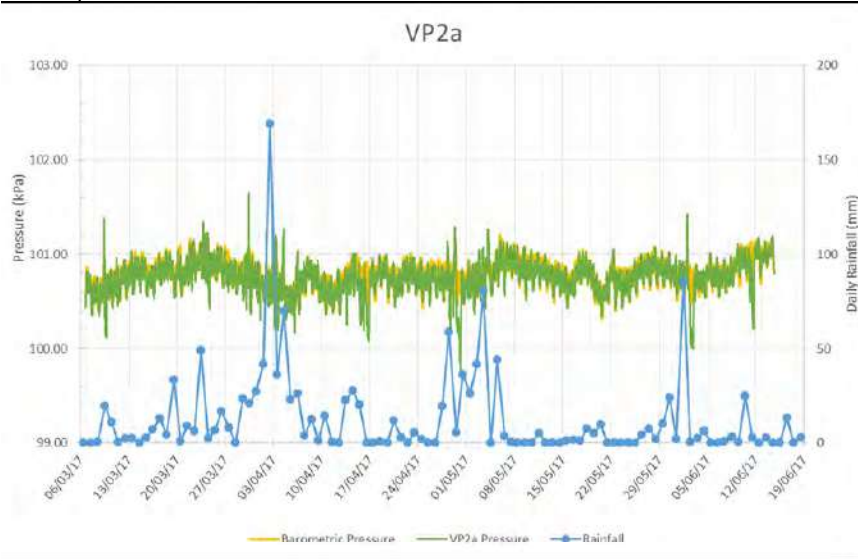
Vapour Pressure 1a



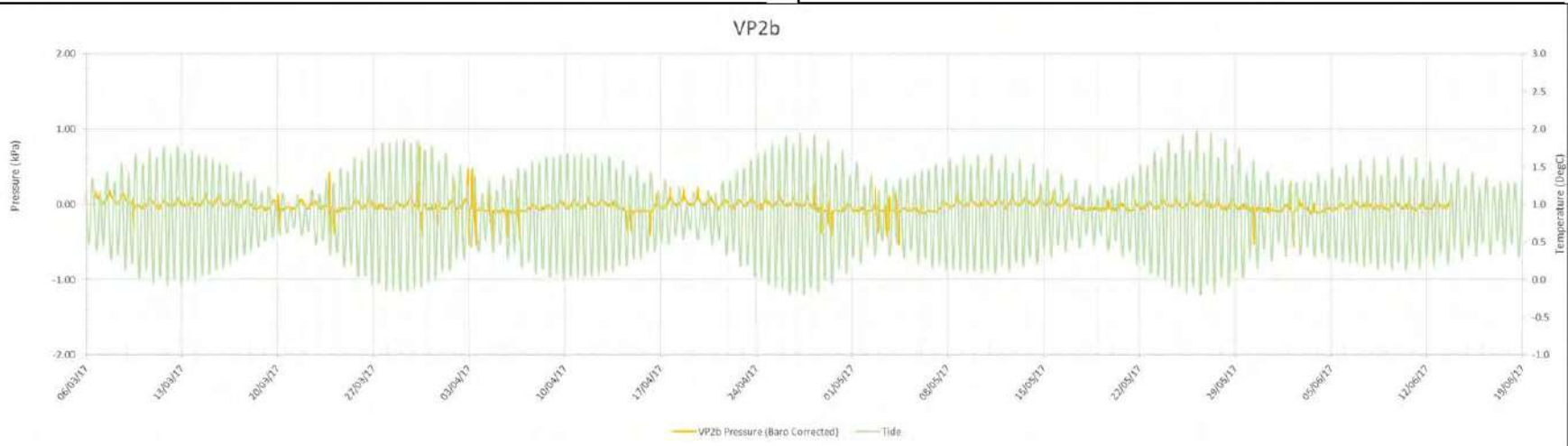
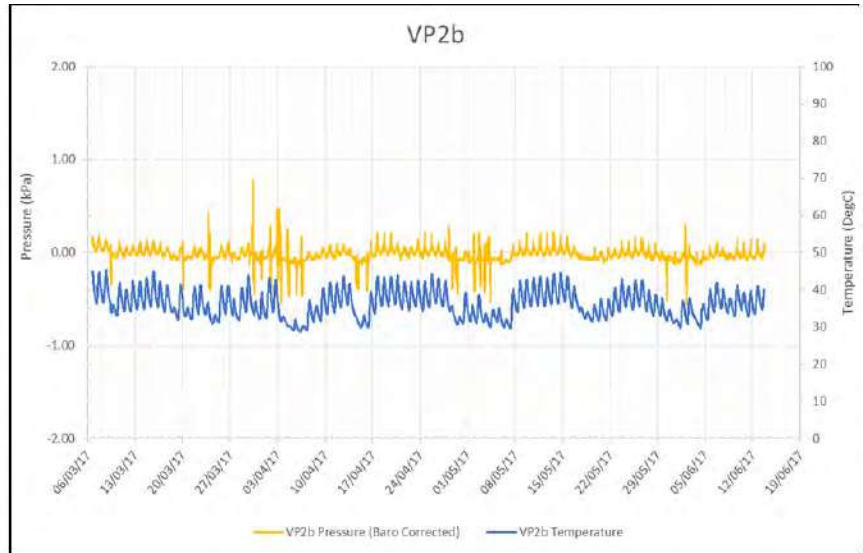
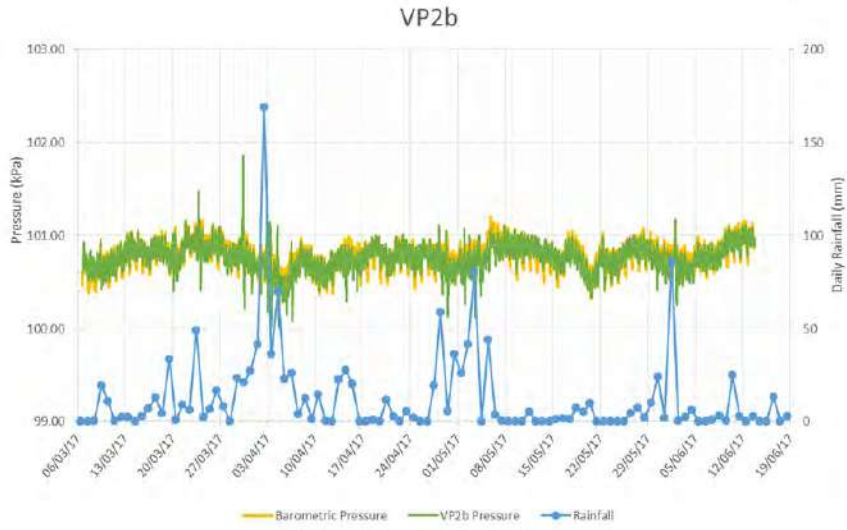
Vapour Pressure 1b



Vapour Pressure 2a



Vapour Pressure 2b



Appendix D: Memorandum of Additional Field Observations

Technical Memorandum

To: Vitoli Iosefa
 From: Glenn Fawcett (TFSU Consultant)
 CC: PAIP Team, James Palmer, Telaulini Niuatui, Dr Theuns Henning
 Date: 10 April 2017
 Re: **RUNWAY DEFECTS ASSESSMENT AND ONGOING MONITORING - TUVALU**

Purpose of Memo This memo summarises the extent of observed delamination/blistering due to pavement voids venting with tidal and atmospheric changes. It presents a baseline upon which local staff can continue to monitor and report the progression of deterioration.

Referencing Method The pavement was divided into 100m sections. Sections were labelled A through P (1550m) along each edge of the runway. Areas of disrupted pavement were identified and marked within each section and progressively numbered A1, A2...B1, B2...etc.



Venting areas can be identified by small bumps in the basecourse. This is most obvious after rain, in evening light or during venting



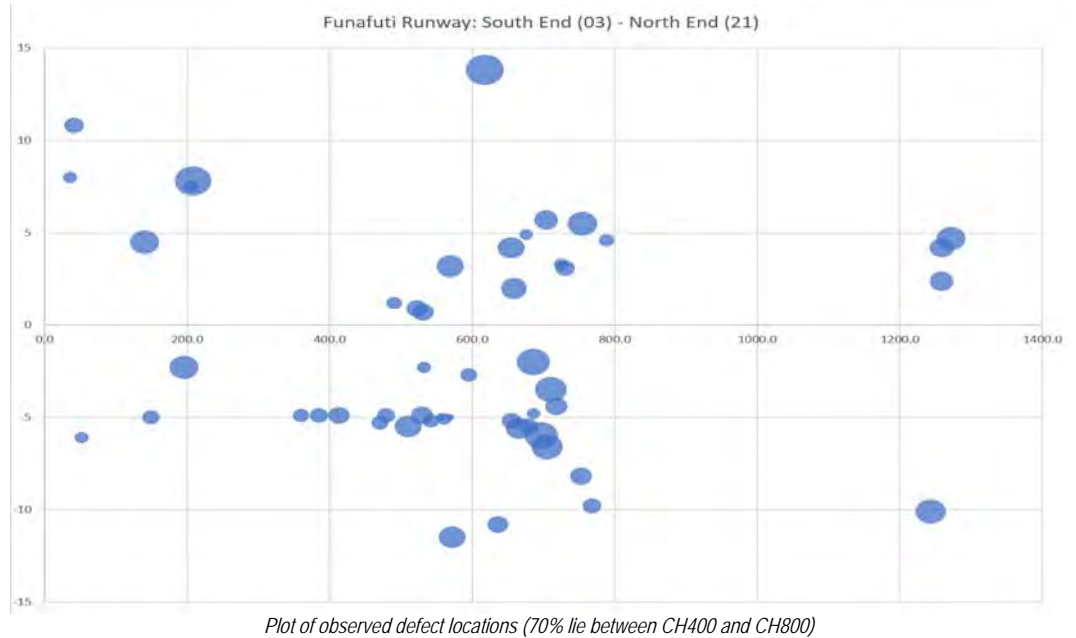
Pavement venting areas marked up. Patches were also inventoried.

Condition in April 2017 During the identification and marking of defects a simple condition rating was assigned to each area. The number and area of defects by condition is summarised below:

Grade	Condition	Area	#
P	Patched section	83.4	14
0	Surface still sound but uneven - monitor	121.6	21
1	Visible loss of waterproofness – monitor weekly	87.0	13
2	Large cracks visible - repair required	13.5	2
Total		222.0	50

Note that the areas marked account for an estimated 70-80% of the defective area likely present. It is extremely difficult to identify all areas as active venting was only observed across 8-10 of the monitoring areas over the two weeks on-island. This could be due to pore pressure activity migrating around the voids or more likely because the optimum conditions were not present during this time (i.e. king tide and rain).

Two areas have suffered a “rupture” of the surface due to the venting movement.



Observed rupture of 3-coat bitumen surface during significant venting (Condition Score = 2)

With hot weather, these ruptures have since settled a little but will require close monitoring and a digout repair over the next 4-6 weeks. Digouts may be smaller (or larger) than the marked monitoring areas and the final extent should be determined as the surface is cut and removed.

Also of significant note is that approximately 70% of the active venting was observed between CH.500m (from RWY03/southern end) and CH.800m and no venting was observed between CH.800 and CH.1550 (end of runway)

Patching Methodology

Auckland University are preparing a longer-term patching and repair solution for this venting phenomenon. Should a repair be needed over the next 4-6 weeks, a 250mm, 30MPa concrete repair solution has been proposed by GHD. Ideally this would be capped with 50mm of AC and there is a small amount available on-island that could be livened up with some kerosene.

Note that some of the digouts could be wider than 2.0m and the smooth placement of hand placed AC will be a challenge and will require supervision. The availability of a steel drum pedestrian roller will help with a more uniform compaction. Previous repairs are uneven as

compaction was carried out with forklift tyres.

Urgent, *temporary patching of small areas* (<0.5m²) could be done by saw cutting and removing the bitumen surface(s) to 50mm and compacting coldmix in 25mm layers. A hand tamper could be used for the lower level with a plate compactor to finish the top level.



Steel drum roller (ex.Reeves)



Plate compactor (ex.PWD)



Hand tamper (to manufacture)

**Ordering
Materials**

Based on the assumption that areas given a condition score of 1 or 2 are likely to fail over the next 6-18 months then material orders should be sufficient to repair around 100m² of pavement. At 50mm deep this **would eventually require around 12T**. Polymer modified cold mix AC can be purchased in 1T bags or in smaller 22kg plastic bags. The smaller plastic bags are sealed and report a longer shelf life up to 12 months. 1T bags will only last several months. It is recommended that an order is placed for a combination of 1T and 22kg bags. This should be coordinated with TEC who will likely require cold mix for upcoming trenching for its new street lights.



Part bag of cold mix AC "stored" in CAA compound

Note that there is a part bag of coldmix (approx. 0.75T) left over from earlier pavement patching in CAA's compound. This mix was still active when inspected and could be livened up further with a small amount of kerosene (amount to be determined through test rolling/compaction).

**Required
Action**

- a) GHD and Auckland University to provide a short and long-term repair methodology.
- b) AC and concrete materials to be ordered and shipped to country. A relatively urgent supply of 3T of cold mix AC in 1T and 22kg bags should be investigated for combination with an order for TEC (street light trenching) or with the concrete order for the Geocell roads project.
- c) Supervision should be provided when initial work is carried out. Trial compaction areas should be established to practice getting a smooth finish and determining the "overfill" height of uncompact mix.

ANNEX A: Extent of Delamination/Blistering

Monitoring of observed venting locations (delamination/blistering) at Funafuti Airport

ID	Side	Dist.	Offset	Length	Width	Area	CONDITION	10-Apr
A1	L	35.7	8	1.9	1.4	2.7		0
A2	L	41.6	10.8	3.0	1.6	4.8		0
A3	R	51.6	-6.1	2.0	1.3	2.6		1
B1	L	140.8	4.5	4.4	2.5	11.0		0
B2	R	149.7	-5	2.6	1.5	3.9		0
B3	R	196.0	-2.3	4.6	2.4	11.0		0
C1	L	206.0	7.5	2.0	1.5	3.0		0
C2	L	208.5	7.8	5.1	3.4	17.3		0
D1	R	359.8	-4.9	2.8	1.3	3.6		1
D2	R	385.3	-4.9	3.7	1.2	4.4		0
E1	R	412.8	-4.9	4.0	1.5	6.0		1
E2	R	470.5	-5.3	2.9	1.3	3.8		1
E3	R	479.1	-4.9	2.9	1.5	4.4		1
E4	L	490.5	1.2	2.4	1.3	3.1		0
F1	R	510.0	-5.5	3.8	2.4	9.1		0
F2	L	522.5	0.9	2.4	2.5	6.0		2
F3	R	529.5	-4.9	2.8	2.2	6.2		1
F4	L	531.0	0.7	2.6	2.2	5.7		2
F5	R	532.5	-2.3	2.2	1.2	2.6		1
F6	R	542.0	-5.2	2.6	1.4	3.6	P	
F7	R	555.3	-5	1.2	0.9	1.1	P	
F8	R	560.3	-5.1	2.0	1.4	2.8	P	
F9	R	568.5	-5	1.5	0.6	0.9	P	
F10	L	569.2	3.2	3.6	2.7	9.7		0
F11	R	572.1	-11.5	3.7	2.5	9.3		1
F12	R	595.0	-2.7	1.8	2.0	3.6	P	0
G1	L	617.6	13.8	8.9	2.1	18.7		1
G2	R	636.3	-10.8	2.8	2.0	5.6		1
G3	L	654.6	4.2	2.8	3.3	9.2		0
G4	R	655.0	-5.2	2.3	2.2	5.1		1
G5	L	658.5	2	2.8	3.1	8.7		1
G6	R	665.2	-5.6	3.0	3.0	9.0		0
G7	L	675.7	4.9	2.0	1.2	2.4	P	
G8	R	678.3	-5.5	2.7	2.0	5.4		1
G9	R	685.8	-2	5.0	2.9	14.5		0
G10	R	685.8	-4.8	2.2	1.1	2.4	P	
G11	R	697.3	-6	4.2	3.4	14.3	P	
H1	L	703.6	5.7	4.0	1.9	7.6		0
H2	R	705.1	-6.6	4.2	3.0	12.6		0
H3	R	710.2	-3.5	3.6	3.6	13.0		0
H4	R	717.5	-4.4	2.8	2.3	6.4		0
H5	L	725.1	3.3	1.6	1.7	2.7		0
H6	L	730.2	3.1	2.8	1.7	4.8		0
H7	R	752.6	-8.2	3.5	1.7	6.0		0
H8	L	754.7	5.5	3.2	3.6	11.5	P	
H9	L	788.5	4.6	2.2	1.4	3.1	P	
H10	R	768.0	-9.8	2.5	1.9	4.8		0
L1	R	1242.6	-10.1	4.3	2.8	12.0	P	
L2	L	1258.2	2.4	3.5	2.1	7.4	P	
L3	R	1258.8	4.2	2.7	2.7	7.3	P	
L4	R	1271.3	4.7	4.6	2.4	11.0	P	
		1550.0	15.0	Monitor Area		347.7		

51				
71%	P	83.4	-	14
	0	-	139.7	23
	1	-	72.6	13
	2	-	13.5	2
		83.4	225.8	52

- Condition Guide**
- 0 Surface still sound but uneven - monitor
 - 1 Visible loss of waterproofness (minor cracks and vents) - monitor
 - 2 Large cracks visible - repair required
 - P Patch repair completed

Appendix E: Cost Estimate for Remedial Work

Item	Name	Unit	Quantity	Rate (US\$)	Amount
1	Short Term Option - Install vertical venting drains as part of the patching strategy to prevent the formation of new venting paths.				
1.1	Preliminary and General	L.S.	1.00	\$ 800,000.00	\$ 800,000.00
1.2	Allowance for earthworks alongside runway to cut a negative slope away from runway	L.S	1.00	\$ 150,000.00	\$ 150,000.00
1.3	Excavation of drainage trenches for subsurface cut-off drains	m3	225.00	\$ 50.00	\$ 11,250.00
1.4	Excavation and installation Runway edge grated drains	m	700.00	\$ 1,000.00	\$ 700,000.00
1.5	Supply Sub-surface Drainage Pipe	m	1,600.00	\$ 6.50	\$ 10,400.00
1.6	Supply Drainage Structures (Manholes and couplings)	L.S	1.00	\$ 6,000.00	\$ 6,000.00
1.7	Repair existing Depressions	item	15.00	\$ 500.00	\$ 7,500.00
1.8	Installation of Instrumentation to monitor pressure and water levels	L.S	1.00	\$ 20,000.00	\$ 20,000.00
1.9	Repair Damaged Surface	m2	20.00	\$ 300.00	\$ 6,000.00
1.10	Provision of venting systems	Item	30.00	\$ 800.00	\$ 24,000.00
1.11	Excavate existing patches 200mm insitu (to waste) and prepare sub grade	m2	120.00	\$ 50.00	\$ 6,000.00
1.12	Installation of vertical venting	Item	20.00	\$ 400.00	\$ 8,000.00
1.13	Patch re-instatement with venting system	m2	120.00	\$ 150.00	\$ 18,000.00
Subtotal Item 1					\$ 1,767,150.00

Item	Name	Unit	Quantity	Rate (US\$)	Amount
2	Medium-Term Option Directional Drilling Install fish-bone subsurface drainage in affected/high-risk areas				
2.1	Preliminary and General	L.S.	1.00	900,000.00	900,000.00
2.2	Allowance for earthworks alongside runway to cut a negative slope away from runway	L.S	1.00	\$ 80,000.00	80,000.00
2.3	Drill 63mm SDR 11 Perferated pipe in coral.	m	3,000.00	500.00	1,500,000.00
2.4	Excavation of drainage trenches for subsurface cut-off drains	m3	140.00	50.00	7,000.00
2.5	Excavation and installation Runway edge, taxiways and side roads grated drains	m	5,000.00	1,000.00	5,000,000.00
2.6	Supply Sub-surface Drainage Pipe	m	3,000.00	6.50	19,500.00
2.7	Supply Drainage Pipe	m	600.00	6.50	3,900.00
2.8	Suply Drainage Structures (Manholes and couplings)	L.S	1.00	600.00	600.00
2.9	Drainage pits to a depth 1.4m backfilled with aggregates	LS	1.00	300,000.00	300,000.00
2.10	Installation drainage system incl backfill	m3	120.00	50.00	6,000.00
2.11	Installaiton of Instrmentaiton to monitor pressure and water levels	L.S	1.00	20,000.00	20,000.00
Subtotal Item 2					\$ 7,837,000.00

Item	Name	Unit	Quantity	Rate (US\$)	Amount
3	Long-term Install fish-bone subsurface drainage in affected/high-risk areas				
3.1	Preliminary and General	L.S.	1.00	\$ 1,600,000.00	\$ 1,600,000.00
3.2	Allowance for earthworks alongside runway to cut a negative slope away from runway	L.S	1.00	\$ 80,000.00	\$ 80,000.00
3.3	Excavation of fish bone drainage trenches (300 mm depth)	m3	2,100.00	\$ 300.00	\$ 630,000.00
3.4	Excavation of drainage trenches for subsurface cut-off drains	m3	210.00	\$ 50.00	\$ 10,500.00
3.5	Excavation and installation Runway edge, taxiways and side roads grated drains	m	1,400.00	\$ 1,000.00	\$ 1,400,000.00
3.6	Supply Sub-surface Drainage Pipe	m	3,000.00	\$ 6.50	\$ 19,500.00
3.7	Supply Drainage Pipe	m	800.00	\$ 6.50	\$ 5,200.00
3.8	Supply Drainage Structures (Manholes and couplings)	L.S	1.00	\$ 16,000.00	\$ 16,000.00
3.9	Drainage pits to a depth 1.4m backfilled with aggregates	L.S	1.00	\$ 300,000.00	
3.10	Installation drainage system incl backfill	m3	1,760.00	\$ 120.00	\$ 211,200.00
3.11	Reconstruct 200mm Base Course formation	m2	21,000.00	\$ 180.00	\$ 3,780,000.00
3.12	Surface reconstructed areas (2 coat surface)	m2	21,000.00	\$ 40.00	\$ 840,000.00
3.13	Installation of Instrumentation to monitor pressure and water levels	L.S	1.00	\$ 20,000.00	\$ 20,000.00
Subtotal Item 3					\$ 8,612,400.00

Appendix F: Assumptions for Cost Estimate

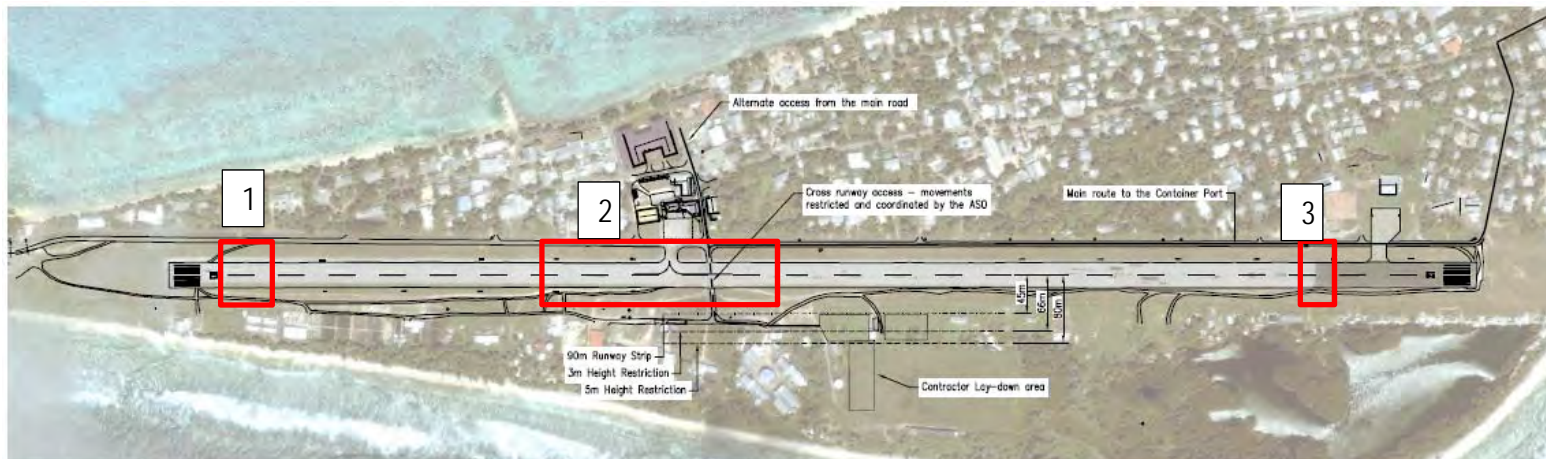


Figure – Indicating the positions for installing Herringbone drainage system

- Runway dimensions for affected areas:
 1. 100m x 30m
 2. 350m x 30m
 3. 50 m x 30m

Note (the exact extent of the areas to be confirmed through pavement tests and detail inspections)

- Fish bone drainage to be spaced 5 m apart and crossing the entire width of 30m
- Trenching to be assumed at 0.5 width
- Sub-surface cut-off drainage parallel to the runway total length of 1,400m
- Length of Runway edge grated drains 1,400m
- Drainage pipe depth 0.4m

Appendix G : Levelogger Technical Specifications

Levellogger Edge Specifications

Level Sensor:	Piezoresistive Silicon with Hastelloy Sensor
Accuracy:	± 0.05% FS (Barologger Edge: ± 0.05 kPa)
Stability of Readings:	Superior, low noise
Units of Measure:	m, cm, ft., psi, kPa, bar, °C, °F (Barologger Edge: psi, kPa, mbar, °C, °F)
Normalization:	Automatic Temperature Compensation
Temp. Comp. Range:	0° to 50°C (Barologger Edge: -10 to +50°C)
Temperature Sensor:	Platinum Resistance Temperature Detector (RTD)
Temp. Sensor Accuracy:	± 0.05°C
Temp. Sensor Resolution:	0.003°C
Battery Life:	10 Years - based on 1 reading/minute
Clock Accuracy:	± 1 minute/year (-20°C to 80°C)
Operating Temperature:	-20°C to 80°C
Maximum # Readings:	40,000 readings FRAM memory, or up to 120,000 using linear data compression
Memory:	Slate and Continuous
Communication:	Optical Infrared Interface. Conversion to RS-232, USB, SDI-12. Serial at 19,200 bps, 38,400 bps with USB
Size:	7/8" x 6.25" (22 mm x 159 mm)
Weight:	4.6 oz. (129 grams)
Corrosion Resistance:	Titanium based PVD coating
Other Wetted Materials:	Delrin®, Viton®, 316L stainless steel, Hastelloy, Titanium based PVD coating
Sampling Modes:	Linear, Event & User-Selectable with Repeat Mode, Future Start, Future Stop, Real-Time View
Measurement Rates:	1/8 sec to 99 hrs
Barometric Compensation:	Software Wizard and one Barologger in local area (approx. 20 miles/30 km radius)

Models	Full Scale (FS)	Accuracy
Barologger	Air only	± 0.05 kPa
F15, M5	16.4 ft., 5 m	± 0.010 ft., 0.3 cm
F30, M10	32.8 ft., 10 m	± 0.016 ft., 0.5 cm
F65, M20	65.6 ft., 20 m	± 0.032 ft., 1 cm
F100, M30	98.4 ft., 30 m	± 0.064 ft., 1.5 cm
F300, M100	328.1 ft., 100 m	± 0.164 ft., 5 cm
F600, M200	656.2 ft., 200 m	± 0.328 ft., 10 cm

Levellogger Junior Edge: See Levellogger Junior Edge Data Sheet.
Conductivity: See Model 3001 LTC Levellogger Junior Data Sheet

DataGrabber

The DataGrabber is a field-ready data transfer device that allows you to copy data from a Levellogger, onto a USB flash drive key.

The DataGrabber is compact and very easy to transport. It connects to the top end of a Levellogger's Direct Read Cable, or an Adaptor is available to allow direct connection to a Levellogger.



One push-button is used to download all of the data in a Levellogger's memory to a USB device plugged into the DataGrabber. A convenient LED light indicates the operation of the DataGrabber. The data in the Levellogger memory is not erased, and logging is not interrupted if the Levellogger is still running. The DataGrabber uses its own replaceable 9V battery.



STS Telemetry

The STS Telemetry System provides an economical and efficient method to send Levellogger data from the field to your desktop. Built for Levelloggers, the system combines high quality dataloggers, intuitive software, and wireless communication, to create a remote monitoring solution.

Communication options give the flexibility to suit any project. Systems are suitable for both small to large networks. STS Systems are designed to save costs by enabling the self-management of data. Alarm notification, remote firmware upgrades and diagnostic reporting make system maintenance simple (see Model 9100/9200 data sheet).

RRL Telemetry

The inexpensive RRL Remote Radio Link is ideal for short range applications up to 20 miles or 30 km; distances can be increased by using some radios as relay stations. Ideal for creating closed-loop monitoring networks using Levelloggers (see Model 9100/9200 data sheet).

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Standard Cable Deployment

Levelloggers may be suspended on a stainless steel wireline or Kevlar® cord. This is a very inexpensive method of deployment, and if in a well, allows the Levellogger to be easily locked out of sight and inaccessible. Solinst offers stainless steel wireline assemblies and Kevlar cord assemblies in a variety of lengths.

Solinst 3001 Well Cap Assembly

The 2" Locking Well Caps are designed for both standard and Direct Read Cable deployment options.

The well cap has a convenient eyelet for suspending Levelloggers using wireline or Kevlar cord. The Well Cap insert has two openings to accommodate Direct Read Cables for both a Levellogger and Barologger. Adaptors are available to fit 4" wells.

The cap is vented to equalize atmospheric pressure in the well. It slips over the casing, and the cap can be secured using a lock with a 3/8" (9.5 mm) shackle diameter.



*Levellogger 2" Locking Well Cap Installations
(see Well Caps data sheet for more details)*

Direct Read Cables

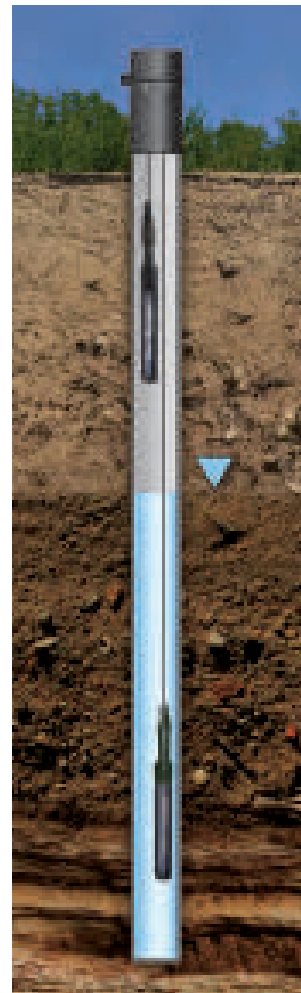
When it is desired to get real-time data and communicate with Levelloggers without removal from the water, they can be deployed using Direct Read Cables. This allows viewing of the data, downloading and/or programming in the field using a portable computer, DataGrabber, or the Solinst Levellogger App and Interface.

Levelloggers can also be connected to an SDI-12 datalogger using the Solinst SDI-12 Interface Cable attached to a Direct Read Cable.

Cable Specifications

Direct Read Cables are available for attachment to any Levellogger in lengths up to 1500 ft. The 1/8" dia. (3.175 mm) coaxial cable has an outer polyethylene (MDPE) jacket for strength and durability. The stranded stainless steel conductor gives non-stretch accuracy.

*Barologger and Levellogger
installed in Well Using
Direct Read Cables*



Accurate Barometric Compensation

The Levellogger Edge measures absolute pressure (water pressure + atmospheric pressure) expressed in feet, meters, centimeters, psi, kPa, or bar.

The most accurate method of obtaining changes in water level is to compensate for atmospheric pressure fluctuations using a Barologger Edge, avoiding time lag in the compensation.

The Barologger is set above high water level in one location on site. One Barologger can be used to compensate all Levelloggers in a 20 mile (30 km) radius and/or with every 1000 ft. (300 m) change in elevation.

The Levellogger Software Data Compensation Wizard automatically produces compensated data files using the synchronized data files from the Barologger and Levelloggers on site.

The Barologger Edge uses pressure algorithms based on air rather than water pressure, giving superior accuracy.

The recorded barometric information can also be very useful to help determine barometric lag and/or barometric efficiency of the monitored aquifer.

The Barologger Edge records atmospheric pressure in psi, kPa, or mbar. When compensating submerged Levellogger Edge, Gold or Junior data, Levellogger Software Version 4 can recognize the type of Levellogger and compensate using the same units found in the submerged data file (Levellogger Gold and Junior measure in feet, meters, or centimeters). This makes the Barologger Edge backwards compatible.

*Synchronize & Streamline Your
Barometric Compensation Efforts,
Across Your Entire Site*



® Kevlar is a registered trademark of DuPont Corp.

Levelogger Setup

Programming Leveloggers is extremely intuitive. Simply connect to a PC using an Optical Reader or PC Interface Cable. All in one screen fill in your project information and sampling regime. Templates of settings can be saved for easy re-use.

The Levelogger time may be synchronized to the computer clock. There are options for immediate start or future start and stop times. The percentage battery life remaining and the amount of free memory are indicated on the settings screen.

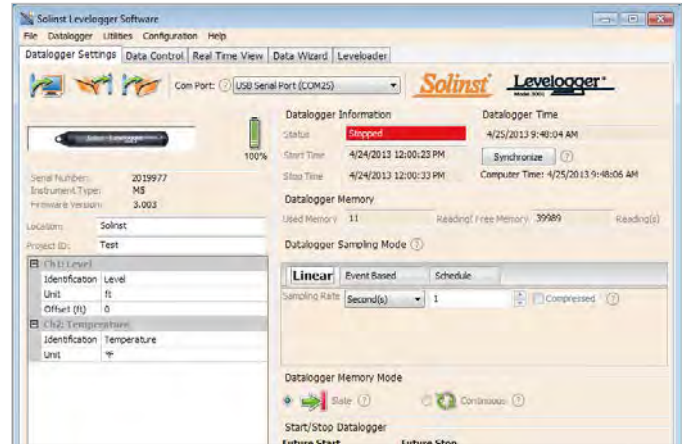
Leveloggers can also be programmed with a sampling regime and start/stop times using the Solinst Levelogger App on your smart device.

Convenient Sampling Options

Leveloggers can be programmed with linear, event-based, or a user-selectable sampling schedule. Linear sampling can be set from 1/8 second to 99 hours. The Levelogger Edge can be programmed with compressed linear sampling, which increases memory from 40,000 to up to 120,000 readings.

Event-based sampling can be set to record when the level changes by a selected threshold. Readings are checked at the selected time interval, but only recorded in memory if the condition has been met. A default reading is taken every 24 hours if no “event” occurs.

The Schedule option allows up to 30 schedule items, each with its own sampling rate and duration. For convenience, there is an option to automatically repeat the schedule.



Levelogger Edge Settings Software Windows

Data Download, Viewing and Export

Data is downloaded to a PC with the click of a screen icon. There are multiple options for downloading data, including ‘Append Data’ and ‘All Data’. The software also allows immediate viewing of the data in graph or table format using the ‘Real Time View’ tab.

The level data is automatically compensated for temperature, and the temperature data is also downloaded. Barometric compensation of Levelogger data is performed using the Data Wizard, which can also be used to input manual data adjustments, elevation, offsets, density, and adjust for Barometric efficiency.

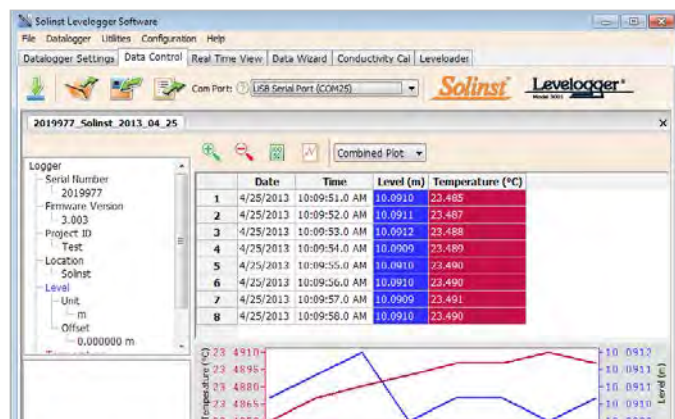
The software allows easy export of the data into a spreadsheet or database for further processing.

The Solinst Levelogger App also allows you to view and save real-time, or logged data right on your smart device.

Helpful Utilities

The ‘Self-Test Diagnostic Utility’ can be used in case of an unexpected problem. It checks the functioning of the program, calibration, backup and logging memories, the pressure transducer, temperature sensor and battery voltage, as well as enabling a complete Memory Dump, if required.

A firmware upgrade will be available from time to time, to allow upgrading of the Levelogger Edge, as new features are added.



Solinst Levelogger App & Levelogger App Interface

The Levelogger App Interface uses Bluetooth® technology to connect your Levelogger to your smart device. With the Solinst Levelogger App, you can download data, view real-time data, and program your Leveloggers. Data can be e-mailed from your smart device directly to your office (see Model 3001 Levelogger App & Interface data sheets).



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Levelogger® Edge

Model 3001

The Levelogger Edge records highly accurate groundwater and surface water level and temperature measurements. It combines a pressure sensor, temperature detector, 10-year lithium battery, and datalogger, sealed within a 7/8" x 6.25" (22 mm x 159 mm) stainless steel housing with Titanium based PVD coating.

The Levelogger Edge measures absolute pressure using a Hastelloy pressure sensor, offering excellent durability and reliability. Combined with the Titanium based PVD coating, both elements have high corrosion resistance in harsh environments, allowing stable readings in extreme pressure and temperature conditions. The Hastelloy sensor can withstand 2 times over-pressure without permanent damage.

The Levelogger Edge features a wide temperature compensated pressure range (0 to 50°C, -10 to 50°C for Barologger Edge), and rapid thermal response time. The Levelogger Edge has high resolution and an accuracy of 0.05% FS. The convenient Barologger Edge provides the easiest and most accurate method of barometric compensation.

Applications

- Aquifer characterization: pumping tests, slug tests, etc.
- Watershed, drainage basin and recharge monitoring
- Stream gauging, lake and reservoir management
- Harbour and tidal fluctuation measurement
- Wetlands and stormwater run-off monitoring
- Water supply and tank level measurement
- Mine water and landfill leachate management
- Long-term water level monitoring in wells, surface water bodies and seawater environments



Fast communication and downloading speeds with a high speed Optical Reader



Features

- 0.05% FS Accuracy
- Corrosion resistant Titanium based PVD coating
- Robust Hastelloy pressure sensor
- Accurate temperature compensation
- Memory for up to 120,000 readings
- Basic and advanced data compensation options

The Levelogger Edge has a battery life of 10 years based on a 1-minute sampling rate. It has FRAM memory for 40,000 sets of data points - or up to 120,000 using the compressed linear sampling option.

The Levelogger Edge uses a Faraday cage design, which protects against power surges or electrical spikes caused by lightning. Its durable maintenance-free design, high accuracy and stability, make the Levelogger Edge the most reliable instrument for long-term, continuous water level recording.

Flexible Communication

Levelogger PC Software is streamlined, making it easy to program dataloggers, and to view and compensate data, in the office or in the field. The software has useful programming options, including compressed and repeat sampling, and future start/stop. Data compensation has been simplified, and allows multiple data files to be barometrically compensated at once.

The extremely intuitive Solinst Levelogger App, and Levelogger App Interface on your in-field Leveloggers, creates a Bluetooth® connection between your Leveloggers and smart device. Also an option, the DataGrabber is a field-ready, USB data transfer unit designed specifically for the Levelogger Series.

For remote monitoring, options include STS Telemetry Systems and RRL Remote Radio Link. In addition, Levelogger Edge Series dataloggers are SDI-12 compatible.