Proceedings of the 7th International Young Geotechnical Engineers Conference – Scott (Ed.)

Designing a breakwater in Apia: Results, challenges and recommendations

Conception d'un brise-lames à Apia: résultats, défis et recommendations

Christoph Kraus & Nicola Ridgley
Beca Ltd, New Zealand, christoph.kraus@beca.com

ABSTRACT: The Port of Apia, Samoa, is undergoing a development project to upgrade its facilities and infrastructure. As part of this project, an extension and remediation of the existing breakwater were assessed to provide further protection from swell waves and cyclones, thereby reducing delays in port operations. To inform the design of the breakwater, three boreholes were drilled in Apia Harbour, each recovering ~20m of very loose/soft sediments overlying basaltic lava flows. This recent borehole data was combined with the historical data to develop a geological ground model of the site. Using the ground model, liquefaction and slope stability analyses were undertaken for the breakwater extension and remediation. Analyses indicate likely liquefaction of the loose sediments leading to lateral displacement of the breakwater. The results were compared with the performance of the breakwater during the 2009 Mw8.1 earthquake. Options to improve the seismic resilience were considered with the emergency preparedness option being taken forward for detailed design.

RÉSUMÉ : Le port d'Apia, à Samoa, fait l'objet d'un projet de développement visant à moderniser ses installations et son infrastructure. Dans le cadre de ce projet, la restauration et extension du brise-lames existant ont été évaluées afin de fournir une protection supplémentaire contre la houle et les cyclones et, ainsi réduire les retards dans les opérations portuaires. Afin d'informer la conception du brise-lames, trois forages ont été réalisés dans le port d'Apia, récupérant chacun ~20m de sédiments meubles déposés sur des coulées de lave basaltique. Ces données de forage récentes ont été combinées aux données historiques pour développer un modèle géologique du site. Des analyses de liquéfaction et de stabilité des pentes ont ensuite été entreprises pour évaluer l'extension et la restauration du brise-lames. Ces analyses indiquent une liquéfaction probable des sédiments meubles entraînant un déplacement latéral du brise-lames. Les résultats ont été comparés à la performance du brise-lames lors du séisme Mw8.1 de 2009. Plusieurs options visant à améliorer la résilience sismique ont été envisagées, mais l'option de préparation aux situations d'urgence a été retenue pour la conception détaillée.

KEYWORDS: Apia, Samoa, breakwater, seismic, liquefaction.

1 INTRODUCTION

The Port of Apia is a commercial port which provides essential transportation links for imports to, and exports from, Samoa. A 100m long breakwater comprising rubble, armour stone and 8t dolosse armour units was constructed in 1988-89 to provide shelter from swell waves affecting vessels berthed at the wharf. Following large cyclones in the early 1990s, the breakwater was repaired in 1996. This included widening using rubble and armour stone, as well as placing larger 20t dolosse armour units. In 2003, a solid concrete crown wall was added to mitigate wave transmission to the harbour basin.

ADB (2017) identified that an extension and remediation of the breakwater was required to mitigate the intrusion of swell waves into Apia Harbour, and therefore reduce delays in port operations. Beca International Consultants was engaged by the Samoa Ports Authority to undertake investigations for the rehabilitation, and possible extension of, the existing breakwater at Apia Port. This paper outlines the outcomes of the geotechnical investigations and the seismic performance issues associated with the breakwater.

2 SETTING

2.1 *Apia Harbour*

Apia is located on the northern coast of the island of Upolu, Samoa. The Port of Apia is located 1.2km northeast of Apia's central business district, at the north-eastern end of Apia Harbour (Figure 1). The water depth of the harbour increases from -1mCD where the Vaisigano River enters the harbour to about -16mCD north of the existing breakwater. The Vaisigano River contributes a significant sediment supply to the harbour, with discharge rates between 10,000 and 45,700m^3/day during floods (Richmond, 1992).

2.2 *Geology and seismicity*

Apia is mapped to be underlain by Holocene-aged alluvium, and the area south of Apia is underlain by the Pleistocene-aged Salani Volcanic Formation (SVF) (Kear et al, 1959). The SVF is characterised by low angle, fine grained basalt lava flows, which grade upward into vesicular basalt. SVF basalt often has a deep weathering profile with soil formation between lava flows (Keating, 1992). The Ma'agi'agi Fault and the Vaisigano Fault are mapped 2km southeast and 1km south of the Port, respectively (Fepuleai & Németh, 2018).

Samoa is located north of the Tonga trench, where the Pacific Plate subducts beneath the Tongan and Australian Plates. Most earthquakes in the region are centred either along the subduction interface or within the subducting slab along the Tonga trench. One such earthquake was the 2009 Mw8.1 earthquake which occurred on or near the outer rise of the subducting Pacific Plate. As the subduction interface dips westward, the focus of earthquakes tends to increase in depth with an increasing distance from Samoa (USGS, 2012; 2019a).

The breakwater was required to be designed in accordance with the National Building Code of Samoa (MWTI, 2017), which refers to NZS1170 (Standards New Zealand, 2004) and NZS4203 (Standards New Zealand, 1992) for earthquake loadings. NZS4203 is a superseded standard and NZS1170 does not specifically provide zone factors for Samoa. The zone factor (0.4) was derived by a comparison between NZS4203 and NZS1170, such that equivalent design actions would be achieved. To satisfy building code requirements, design seismic peak ground accelerations were derived from both NZS4203 and NZS1170 for comparison (Table 1).

Table 1. Derived peak ground accelerations (PGAs) and annual probability of exceedance (APE).

Standard	SLS		ULS	
	APE	PGA at T=0	APE	PGA at T=0
NZS4203	1/10	0.07 (0.117) [a]	1/100 (1/450) [a]	0.42 (0.70) [a]
NZS1170	1/25	0.112	1/100 (1/500) [b]	0.22 (0.45) [b]

[a] Values in brackets refer to building classification/risk factor IV. Values not in brackets refer to building classification/risk factor V
[b] Values in brackets to importance level IL2. Values not in brackets refer to IL1

3 SITE INVESTIGATIONS AND GROUND MODEL

Three boreholes were drilled in 2018 to the west of the existing breakwater using a QM200 rotary rig, aboard the jack-up barge Tuhura. Testing comprised standard penetration tests (SPTs) and shear vanes in cohesive sediments. Laboratory testing (gradings and Atterberg limits) was completed to confirm the sediment grain size and plasticity. Data from historical investigations at the Port, including at the site of the existing breakwater and wharf, was also used. Investigation locations are shown in Figure 1.

Figure 1. Map of Apia Port. Red and black symbols show the locations of investigations completed as part of this project, and black symbols show the locations of historical investigations. The inset map shows the locations of the port and Vaisigano River in Apia.

The ground profile based on the 2018 investigations consists of approximately 20m of Quaternary Marine Sediments overlying two basaltic lava flows which are separated by a 5m thick zone of completely weathered basalt (Figure 2). The marine sediments have been divided into two units; a silty sand (Qms.1) and sandy silt (Qms.2). The ground profile is summarised in Table 2.

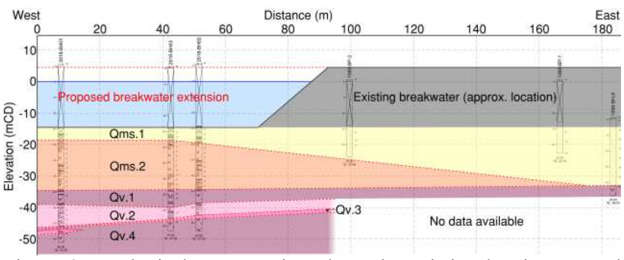

Figure 2. Geological cross-section along the existing breakwater and previously proposed extension.

Table 2. Ground profile at the breakwater.

Geol. Unit	General Description	Vane shear strength (kPa)	SPT N-value
Qms.1	Very loose, silty SAND, trace to some shell fragments, trace organics, trace to no clay; grey; low-no plasticity.	N/A	0
Qms.2	Very soft-soft, sandy SILT, minor-no clay, trace-some shell fragments, trace-no organics; grey; low-no plasticity.	3-27 (typical 15-18)	0-15 (typical 0)
Qv.1	Moderately strong to strong, SW-UW, dark grey BASALT.	N/A	50+ / Refusal
Qv.2	Soft, gravelly SILT / silty GRAVEL, minor-some sand, trace - minor clay; brown; low-high plasticity.	30	0-12 (typical 0-3)
Qv.3	Very weak to moderately strong, MW-HW, brown BASALT.	N/A	50+ / Refusal
Qv.4	Moderately strong to strong, SW-UW, dark grey BASALT.	N/A	50+ / Refusal

The 2018 ground profile is generally consistent with previous investigations. However, the boreholes at the site of the existing breakwater (drilled in 1988) indicate the sand layer (Qms.1) to be thicker and have higher SPT values than was encountered in the 2018 boreholes.

Boreholes drilled further south along the wharf extension, and into the outlet channel from the Vaisigano River, in 2014 and 2016 also encountered about 20-25m of silty sands (SPT typically 0-1) overlying basalt. The ground profile from these 2014/16 boreholes is consistent with the 2018 investigations, and the presence of the loose soils is likely due to the boreholes being located in the outlet channel of the Vaisigano River (due to the high sediment discharge rates).

Similar to the boreholes at the breakwater, the SPT N-values recorded in the 1988 boreholes along the wharf were consistently higher than those recorded in the more recent (2014-2016) investigations. Given (i) the consistency of SPT N-values recorded in the investigations between 2014 and 2018, (ii) the fact that low SPT N-values would be expected based on the high sediment supply rates from the Vaisigano River, and (iii) that some of the recent investigations were completed only a few metres away from the locations of boreholes drilled in 1988 (allowing for a direct comparison), it appears that non-reliable SPT tests were undertaken during the 1988 investigations.

4 RESULTS

4.1 *Liquefaction susceptibility*

The seismic performance of the sediments at the site were assessed based on (i) sediment descriptions, (ii) SPT data, and (iii) laboratory testing (plasticity index). The plasticity index (PI) is widely recognised as a reliable determinant of liquefaction potential. The split in soil behaviour is; PI<7: 'sand-like'; 7≤PI≤12, 'transition', PI>12, 'clay-like'. Soils with PI<12 may be susceptible to liquefaction, while soils with PI>12 are considered non-liquefiable but may be susceptible to cyclic softening (NZGS & MBIE, 2016). Past performances of soils in earthquakes were also considered, as loose sands have liquefied at PGAs as low as 0.05 to 0.1g (de Magistris et al., 2014).

Qms.1 sediments are very loose (Table 2) and exhibit sand-like behaviour (Figure 3). As such the Qms.1 sediments may liquefy under low levels of seismic shaking. Qms.2 sediments are typically very soft to soft and predominantly comprise sandy silt (Table 2). Above about -30mCD, Qms.2 sediments exhibit sand-like to transitional behaviour (Figure 3), and as such may liquefy under low levels of seismic shaking. Below -30mCD, the soil behaviour is more 'clay-like' and these sediments are therefore are considered non-liquefiable but may be susceptible to cyclic softening due to their low strength.

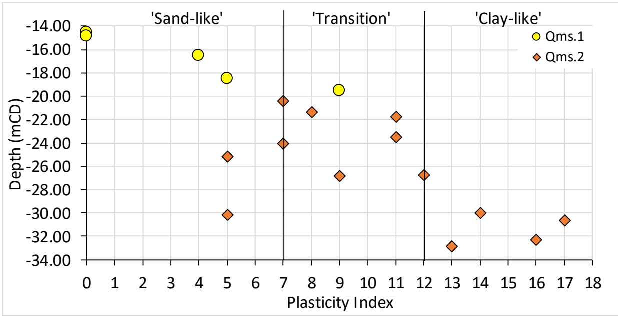

Figure 3. Plasticity index and soil behaviour of Qms.1 and Qms.2 samples with depth.

4.2 *Slope stability and predicted displacement*

Global slope stability analyses were undertaken for the repaired and extended breakwaters using the Morgenstern and Price limit equilibrium method in Slope/W. The SHANSEP model (stress history and normalised soil engineering properties) was used to model liquefied conditions after seismic shaking. Under liquefied conditions Qms.1 and Qms.2 were assigned a liquefied strength ratio (s_u/σ) of 0.1.

Assessments of the long-term static stability of the repaired and extended breakwaters indicate it to meet the requisite factor of safety (>1.5). Under earthquake shaking, yield PGAs of 0.06-0.1g and 0.01-0.03g were determined for non-liquefied and partially liquefied soil conditions, respectively. Moreover, under low levels of shaking and fully liquefied soil conditions, flow failure and lateral spreading of the breakwater may occur (Figure 4).

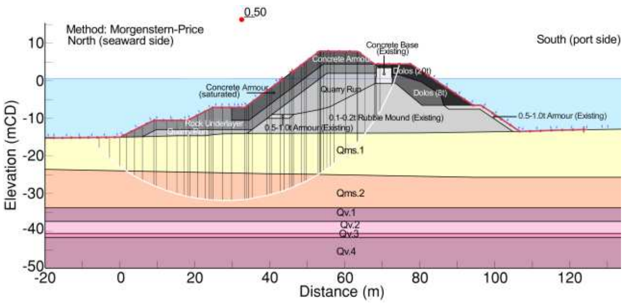

Figure 4. Slope stability analysis for the rehabilitated breakwater with Qms.1 and Qms.2 fully liquefied.

Several methods have been used to assess the seismic displacement of the remediated breakwater. The two main differences in the assessment methods are based on:

- Soils are not liquefied or partially liquefied (under yield acceleration). Analyses were undertaken using conventional slope stability analyses (determination of yield acceleration), and seismic displacements were assessed. These typically ranged between 50 and 900mm.
- Soils are fully liquefied, resulting in flow failure (no yield acceleration). Analyses were undertaken using a range of relationships, resulting in estimates ranging from 3m to >5m of movement. Due to limitations in the applicability of these methods for these soils and breakwater form, there is substantial uncertainty and a low level of accuracy associated with the assessment of lateral spreading displacements.

5 DISCUSSION

5.1 *Lessons from the 2009 Mw8.1 Earthquake and risk from future earthquakes*

The Quaternary Marine Sediments were assessed to be liquefiable at low levels of earthquake shaking with flow failure (lateral spreading) possible under fully liquefied soil conditions. As large earthquakes have affected Samoa in the past, the effect of the 2009 Mw8.1 earthquake in Apia was investigated to further understand the seismic hazard to the port.

There is only one seismometer installed in Samoa (Station 'IU AFI' Afiamalu, Samoa), which has been operational since 1993. It is located about 10km south of the breakwater in the central mountains of Upolu, and situated on basalt rock (USGS, 2019b). Given that the seismometer is situated on rock and the breakwater is situated on very loose/soft sediment, as well as the distance between the seismic station and the harbour, the PGAs measured at this station are not directly applicable to those experienced at the site of the breakwater.

However, the US Geological Survey (USGS) has estimated that a PGA of around 0.08g was experienced in Apia during the 2009 Mw8.1 earthquake (USGS, 2019a). This PGA was derived by using indirect and direct data, including felt intensities reported by the public and the PGA measured at the seismic station in central Upolu (0.0935g). It is not known whether the PGA was estimated for sites on rock or soil. Given the above factors, there is considerable uncertainty relating to this PGA value.

An equivalent PGA at magnitude 7.5 (the design earthquake magnitude) would be about 0.09g for the 2009 Mw8.1 earthquake, based on a magnitude scaling factor of 0.85 (Idriss and Boulanger, 2008). As there was no reported damage or movement of the existing breakwater from this earthquake and given the uncertainty for the PGAs derived for design and the 2009 earthquake, the following conclusions are drawn for SLS events (PGA between 0.07-0.117g):

- At 0.07g the likelihood of widespread liquefaction and lateral spread occurring is assessed to be low. Any seismic displacements of the breakwater are likely to be minimal (less than 100mm).
- At 0.117g there is a risk that liquefaction could occur, resulting in some reduction of the strength of the underlying soils. However, a reduction in soil shear strength to fully liquefied conditions, resulting in lateral spreading, is considered unlikely. Nevertheless, seismic displacements on the order of 100mm to 900mm could be expected assuming partial liquefaction.

At this level of movement, the crest of the remediated breakwater would be expected to remain above its current existing level. However, localised repairs would be necessary to bring the breakwater back to its new design level over the full length to protect against large storm events.

During a ULS earthquake, widespread liquefaction of the underlying soils would be expected to occur, resulting in significant lateral spreading of the breakwater. As a result, the breakwater would be subject to overtopping should a storm or cyclone occur before the breakwater has been remediated.

5.2 *Seismic resilience options & chosen design*

To address the risk of liquefaction and seismic displacements various options to improve the seismic resilience of the breakwater have been considered (Table 3).

Due to cost, environmental and other constraints the ground improvement and rock berm options were not taken further. It is however recommended that a seismic monitoring and emergency response plan is prepared. This plan could include:

- installing seismometers and earthquake monitoring systems. As the only seismometer in Samoa is in the central mountains of Upolu, the installation of a second seismometer at the port to monitor earthquake shaking would be beneficial to both, the port and other structures in Apia.

- a repair response plan detailing how to (i) retrieve dolosse units, (ii) relevel and raise the breakwater, and (iii) replace the dolosse units in a relatively short time period. This may require stockpiling rock and armour units and having a crane accessible at short notice.

Table 3. Seismic resilience design options.

Design Option	Benefits	Limitations
Maintain the breakwater design without mitigation measures (i.e. ground improvement or rock berm)	- Lowest cost	- Risk of damage must be accepted - Repairs after SLS & ULS shaking likely required
Ground improvement comprising *in-situ* stabilised sediments around perimeter of the breakwater	- Greatest protection against earthquake-induced damage	- Very expensive - Ship access to the Port restricted during construction due to construction plant size - Specialist plant required for construction
Extension of the rock berm around the perimeter of the breakwater	- Moderate cost - Provides some further protection	- Environmental considerations, due to a greater area of seabed being covered - Shipping channels and berths compromised

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE PROJECTS

The seismic design of the breakwater was a significant challenge owing to 15m of liquefiable very loose/soft sediment at the site, the scarcity and uncertainty of seismic records and local seismic standards, and the location of the site.

However, using a combination of analyses and learnings from the 2009 Mw8.1 earthquake, we conclude that some liquefaction could occur at SLS-level shaking (about 0.117g), and that widespread liquefaction, resulting in significant lateral spreading of the breakwater, is expected under ULS-level shaking. To provide mitigation against the potential effects of breakwater displacement in an earthquake event, we recommend that a seismic monitoring and emergency response plan is implemented.

In order to reduce some of uncertainties noted above, which are often associated with work at remote sites, the following recommendations are provided for future projects:

- Undertaking a site-specific hazard study to quantify the seismic hazard, particularly where there is no code or guideline available.
- Often only drill rigs are deployed to remote locations due to the costs of deploying separate drill and CPT rigs. Deploying a drill rig with multiple capabilities (e.g. coring and CPTs) requires only the cost of one rig but offers borehole and continuous *in-situ* CPT data to be retrieved.

7 ACKNOWLEDGEMENTS

We would like to thank the Samoa Ports Authority for their support in presenting this work. We also acknowledge Pro-Drill and Heron Construction for their work during the investigations.

8 REFERENCES

ADB (2017). *Draft Engineering Feasibility Study*. TA8889-SAM - Samoa Port Development Project. Asian Development Bank, Manila.

de Magistris, F. S., Lanzano, G., Forte, G., and Fabbrocino, G. 2014. A peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy). *Natural hazards* 74 (2), 1069-1094.

Fepuleai, A., and Németh, K. 2018. Volcanic geoheritage of landslides and rockfalls on a tropical ocean island (Western Samoa, SW Pacific). *Geoheritage* 11 (2), 577-596.

Idriss, I.M., and Boulanger, R.W. 2008. *Soil liquefaction during earthquakes*. Earthquake Engineering Research Institute, 262pp.

Kear, D., Wood, B.L., and Brothers, R.N. 1959. The geology and hydrology of Western Samoa. *New Zealand Geological Survey Bulletin* 63, 1-92.

Keating, B.H. 1992. The geology of the Samoan Islands. in Keating, B. H., and Bolton, B.R. eds., *Geology and Offshore Mineral Resources of the Central Pacific Basin*, Springer, New York, NY, 127-178.

MWTI. 2017. *National building code of Samoa*. Ministry of Works, Transport and Infrastructure (MWTI), Apia.

NZGS, and MBIE 2016. Earthquake geotechnical engineering practice. Module 3: Identification, assessment and mitigation of liquefaction hazards. NZGS and MBIE, Wellington, 38 pp.

Richmond, B.M. 1992. Coastal geology of Upolu, Western Samoa. in Keating, B. H., and Bolton, B. R. eds., *Geology and Offshore Mineral Resources of the Central Pacific Basin*, Springer, New York, NY, 101-125.

Standards New Zealand. 1992. *NZS4203:1992 Volumes 1&2 - General structural design and design loadings for buildings*. Standards New Zealand, Wellington.

Standards New Zealand. 2004. *NZS1170.5:2004 Structural Design Actions - Part 5: Earthquake design actions - New Zealand*. Standards New Zealand, Wellington.

USGS. 2012. *Seismic hazard of American Samoa and neighboring South Pacific Islands—Methods, data, parameters, and results*. U.S. Geological Survey Open-File Report 2012–1087. U.S. Geological Survey, Reston, VA, 98pp.

USGS. 2019a. *M8.1 – Samoa Island region*. <https://earthquake.usgs.gov/earthquakes/eventpage/usp000h1ys/executive>

USGS. 2019b. *Station IU AFI*. <https://earthquake.usgs.gov/monitoring/operations/stations/IU/AFI/>