Seismic design of an XblocPlus® revetment using multi-model approach

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ABSTRACT

When designing and constructing revetments, there is often a drive to reduce the footprint due to space constraints and a limited supply of suitable rock armour materials. Concrete armour units present a potentially more sustainable solution to revetment construction than traditional rock armour. These units are constructed from concrete in a specifically designed configuration to interlock and remain stable at steep slope angles while providing enhanced coastal performance. However, these units have had limited application in seismically active areas. The seismic behaviour of the revetment and the concrete armour units has been assessed to understand the performance during and following earthquake shaking.

XblocPlus® units have been adopted as the armouring for a major shared path project along the shores of Te Whanganui-a-Tara (Wellington Harbour). Understanding the various mechanisms of displacement and the performance of the revetment during and after a seismic event was crucial in determining whether the units would be a viable alternative. This paper discusses the different models used to understand seismic performance and inform the design.

1 INTRODUCTION

A major shared path link is being created along the shores of Te Whanganui-a-Tara (Wellington Harbour) to connect Ngā Ūranga and Pito-One. Granular reclamation fill will provide a platform for the shared path and other recreational areas along the route. An armoured revetment structure is required to protect the reclamation from wave attack over the structure's design life. The revetment will reduce the wave overtopping to acceptable levels for path users during typical and extreme storm events. As sea levels rise, the revetment structure needs to be able to be adapted in the future. Sections 2.1 and 2.2 below discuss the site conditions and planned revetment.

Lateral displacement of the revetment during a design seismic event is expected. The project’s minimum requirements (PMR) require that any damage associated with this displacement can be efficiently repaired. The seismicity and liquefaction hazard of the site and seismic performance criteria of the revetments are discussed in Sections 2.3 to 2.5. The response of XblocPlus revetments to seismic shaking is complex and not easily assessed using a single method or model. Section 3 discusses the multi-model approach that has been used to assess the likely behaviour during and after a design earthquake event.

2 SITE DESCRIPTION AND PROPOSED RECLAMATION

2.1 Site description and geology

The shared path alignment is proposed to be on reclaimed land adjacent to State Highway (SH)2 and the railway corridor, which sits on a relatively narrow bench underlain by a wave-cut shore platform. The platform was uplifted by approximately one metre during the 1855 Wairarapa earthquake. Uplift improved what was, prior to this 1855 event, a narrow and low-lying access between Ngā Ūranga and Pito-One. Reclamation in the first half of the 20th century was carried out to adapt the natural shoreline to the geometric requirements of the transport corridor alignments. The reclamation fill mostly consists of loose to dense sandy gravel with minor silt and cobbles.

Holocene marine deposits underly the existing reclamation fill along the shared path alignment and extend as subtidal deposits forming the seabed. The composition of the marine deposits varies slightly along the length of the revetment. It is dominated by sandy fine to coarse gravels to fine-to-coarse sands with silts and cobbles. The area's published geology (Begg and Mazengarb, 1996) describes the basement geology as interbedded sandstone and argillite (mudstone and siltstone) with occasional conglomerate, pillow basalts and limestone. The underlying bedrock below the marine sediments is generally shallow (from 0 to about 2 m), and mudstone is the most dominant rock along the revetment.

2.2 XblocPlus® revetment

Traditionally, rock is used as revetment armour material to protect coastal land and infrastructure. However, XblocPlus® concrete blocks (DMC 2018) were assessed to provide better outcomes for the project. The key merits of using XblocPlus on this project included:

- The blocks can be placed at steeper slope angles (1.5H:1V batter) than rock armour (typically 2H:1V), resulting in a smaller footprint and reduced coastal occupation.
- The limited availability of suitable quantities and sizes of rock materials in the region for use as primary armour. In addition, the concrete armour units present a potentially more sustainable solution to revetment construction than rock armour material, especially when the primary rock armour units' sourcing, transporting and handling is factored in.
- The pattern-placed XblocPlus units were more efficient and cost-effective than the earlier Xbloc® units with random placement.
- The units’ top form can be modified to improve aesthetics, and the facing of lower units can also be modified to achieve improved ecological outcomes.

The revetment features a slope profile overlain with geotextile filter fabric, two layers of secondary armour (underlayer) rock and 1.0 m^3 XblocPlus as primary armour. The typical toe detail required for stability and mitigation of scour risk comprises a single layer of rock armour (W_{50} = 1.5 T) over two layers of secondary armour (W_{50} = 170 kg). At locations where the toe encounters in-situ rock and requires keying into rock, larger rock (W_{50} = 2.5 T) is proposed for toe armour. Secondary armour extends offshore of the toe armour rock to mitigate expected seabed scour. Geotextile filter fabric extends to the seaward edge of the primary toe armour layer to prevent migration of fine sands and to mitigate the settlement risk of these toe units, which provide support to the base row of XblocPlus units. Figure 1 below shows an isometric rendered view of an XblocPlus revetment and a typical ground model of the reclamation and existing ground conditions.

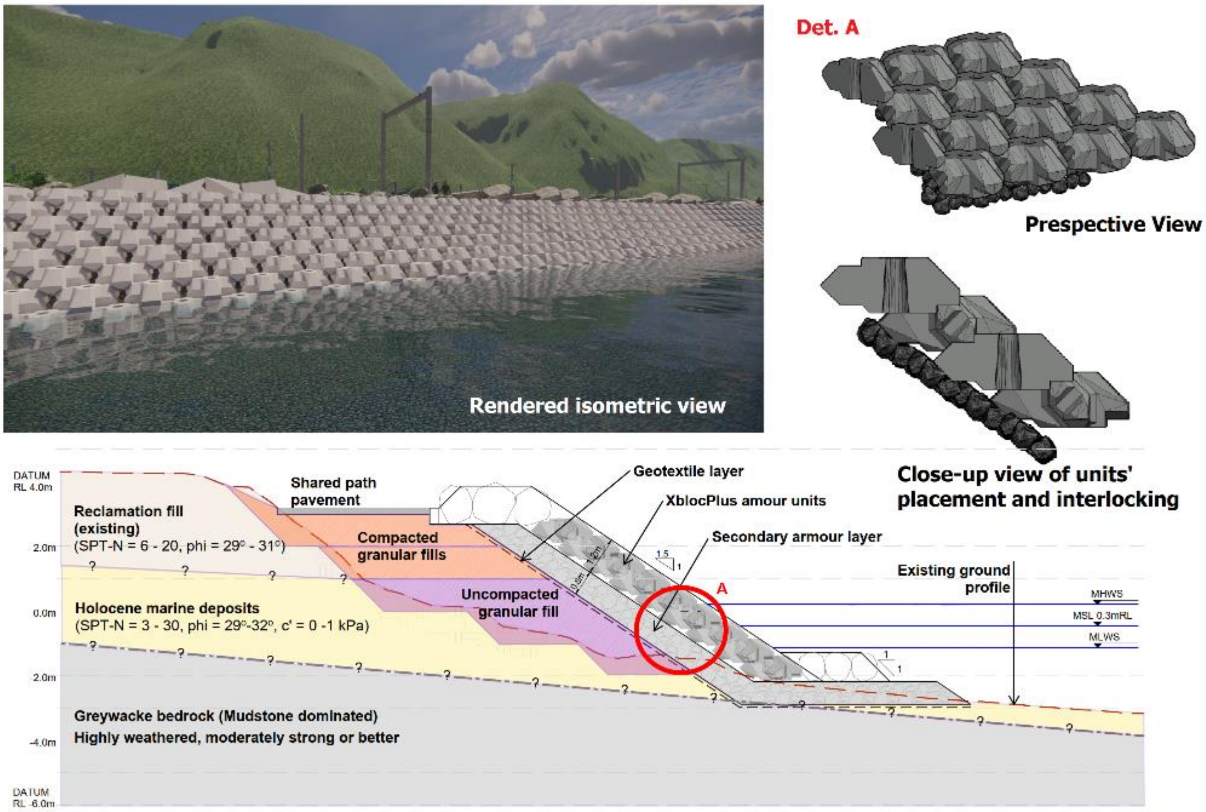


Figure 1. Rendered image of the XblocPlus® units and typical ground model of the revetment

2.3 Design seismic events

Te Whanganui-a Tara (Wellington harbour) is situated on the boundary between two tectonic plates. It lies where the Pacific tectonic plate to the east is being subducted beneath and sliding past the Australian Tectonic plate to the west. This plate boundary and subduction movement have resulted in a series of active faults developing in the region, including the Wairarapa Fault, which ruptured in 1855 (GNS 2020) and the Wellington Fault. The Wellington Fault is particularly pertinent to the Project due to its proximity to the site, which is between 100 and 600 m offshore of the proposed shared path. The Hikurangi subduction zone, especially its Wellington segment, also contributes significantly to the hazard at the site.

The revetment is an importance level 2 (IL2) structure based on the PMR and NZTA Bridge Manual (NZTA BM, amendment 4). A probabilistic seismic hazard assessment (PSHA), which used the 2010 National Seismic Hazard Model, was undertaken for the Project to assess the seismic hazard and determine the ground motion parameters for the site. Table 1 presents the seismic shaking hazard in terms of peak ground acceleration (PGA) and Magnitude used in the design.

Time history selection and scaling were undertaken in general accordance with the requirements of NZS1170.5:2004 Clause 5.5.2 to aid with dynamic analyses and shake table testing. A suite of records was selected and scaled to the 500-year return period uniform hazard spectra using a target period of 0.05 s, which was considered appropriate for short-period structures, such as the revetments. Ground motions with a similar spectral shape to the target spectra over the period range of interest and with similar ground conditions (i.e. similar V_{s30}) were selected. Ground motions were also selected from events within the same tectonic regime (subduction interface and shallow crustal) and consistent magnitudes and fault distances as those expected to control the target spectrum at the dominant periods of interest.

2.4 Liquefaction assessment

A liquefaction assessment was carried out using geotechnical information from offshore investigations at the toe of the proposed revetments. The reclamation fill within the existing transport corridor is mostly above the mean sea level and is not expected to liquefy. Beneath the reclamation fill, the Holocene marine sediments are a mix of sandy to gravelly material, that is expected to be susceptible to liquefaction, and high density (SPT-N > 50) gravels (with fines content less than 5%) that are not predicted to liquefy. The design has assumed that the dense cobbles and gravels are discontinuous infills between the rock outcrops and therefore the marine sediments have been modelled as having continuous layers that would trigger liquefaction.

The triggering of liquefaction has been assessed in accordance with the procedure of Idriss and Boulanger (2014). This method is based on empirical relationships with the SPT-N and fines content. Based on the assessments, liquefaction has been assessed as possible at 0.19 g or higher (33% Ultimate Limit State shaking). Widespread liquefaction could be expected where the marine sediments are continuous. Liquefaction assessment results are summarised in Table 1, presenting the proportion of marine sediment thickness liquefying and the estimated free field ground settlement.

Table 1. Summary of liquefaction analysis results for the revetments

(Results for P_L = 50%)*	**SLS (25-year event)**	**ILS (100-year event)**	**ULS (500-year event)**
Seismic shaking hazard (IL2)	0.12g M6.34	0.29g M7.04	0.60g M7.23
Proportion of marine sediments liquefying	N/A	0 to 60%	0 to 100%
Free field ground settlement (SV1D)	N/A	< 10 mm	< 50 mm

*P_L = probability of liquefaction, *SLS* = serviceability limit state, *ILS* = intermediate limit state (a more frequent event between SLS and ULS where trigger has occurred for most layers), *ULS* = ultimate limit state.

As the proposed revetments will form the seaward face of the existing reclamation fill, lateral spreading is the major consequence of liquefaction at the site. Large ground displacement laterally towards the harbour could be expected in the event of widespread liquefaction. Liquefaction induced ground settlement could also be expected, as presented in Table 1. As there is no crust layer and due to shallow depths of liquefaction, sand boils, and ejecta could also be expected. These will result in ground settlement in addition to the free field ground settlement. However, due to the limited thickness of the marine sediments, significant liquefaction-related settlements, sand boils, or ejecta are not expected.

2.5 Performance requirements

XblocPlus units have had limited application in seismically active areas, so the seismic performance needed to be assessed to use them on the Project. Understanding the performance of the blocks and the underlying revetment fill during and after a seismic event was crucial in determining whether the units would be a viable alternative to rock. The seismic performance of the revetments was checked against the performance requirements prescribed by the PMR (refer to

Table 2 below).

Table 2. Seismic performance criteria for revetments

Event	**Criteria**	**Remarks**
SLS (safety)	FoS > 1.0	- Acceptable damage

Event	Criteria	Remarks
SLS (deformation)	Table 6.1 NZTA BM $u_y < 50$ mm, $\Delta < 1/100$ (slopes)*	- No damage to primary structural members. - Damage to secondary and non-structural elements shall not be such as to impede the operational functionality of the structure.
ULS (safety)	FoS < 1.0, but with acceptable deformation	- Damage is possible, but capable of permanent repair. - No collapse of the structure. - Possible to be reinstated after the event to full functionality.
ULS (deformation)	Table 6.2 NZTA BM Damage is possible	
ULS, Post-EQ, immediate	FoS > 1.1	- Stable with residual shear strengths and zero peak ground acceleration.

*u_y = vertical settlement, Δ = differential settlement.

3 ASSESSMENT METHODOLOGY

3.1 Broad methodology

The expected response of the revetment asset to seismic shaking, particularly the interlocking XblocPlus revetment units, is complex and could not be fully assessed using a single method or model. Damage to the revetment, as a result of earthquake shaking, is expected to be one or a combination of the following:

- Displacement of the reclamation fills resulting in the displacement of the overlying blocks,
- Displacement (sliding and rotation) of individual blocks during seismic shaking, and
- Post-earthquake displacement of the individual blocks due to wave loading on deformed profile.

Therefore, a suite of complementary models was used to assess these mechanisms and understand the most likely *general behaviour* of the revetment asset under the design earthquake events. The approach taken to assess performance is set out in Figure 2 below. It includes assessing the seismic deformation of the revetment core profile using geotechnical analysis, the response of XblocPlus units to this deformation and the response of XblocPlus to the specific shaking itself. The combination of these outputs has been used to develop a possible post-seismic condition (profile) of the revetment.

This condition was then used to assess hydraulic performance if a storm occurred prior to the revetment's repair. Findings and results from these assessments were then used to develop a post-event repair strategy to demonstrate compliance with the PMR. The post-earthquake performance is not part of this paper.

3.2 Geotechnical modelling

Geotechnical analyses were undertaken to check the stability of the revetments under different static and seismic loading conditions. Two general types of analyses were undertaken: slope stability modelling (limit equilibrium modelling) and dynamic numerical (finite element) modelling. These two analysis methods are described in more detail below. In both, the XblocPlus blocks were considered a surcharge loading only, i.e. no shear strength contribution was included from the XblocPlus layer. For the design of the revetments this was a conservative but necessary simplification because the interaction between the blocks is difficult to model accurately in geotechnical analyses.

3.2.1 Limit equilibrium

A slope stability assessment was carried out to check the following:

- The global slope instability or local shallow slips, translational/block or circular type mechanisms;

- Local stability of the secondary armour with the XblocPlus loading;
- Effect of hydraulic conditions (changing tidal planes) on the revetment stability; and
- Seismic displacements following a ULS shaking and assuming Newmark sliding block displacements.

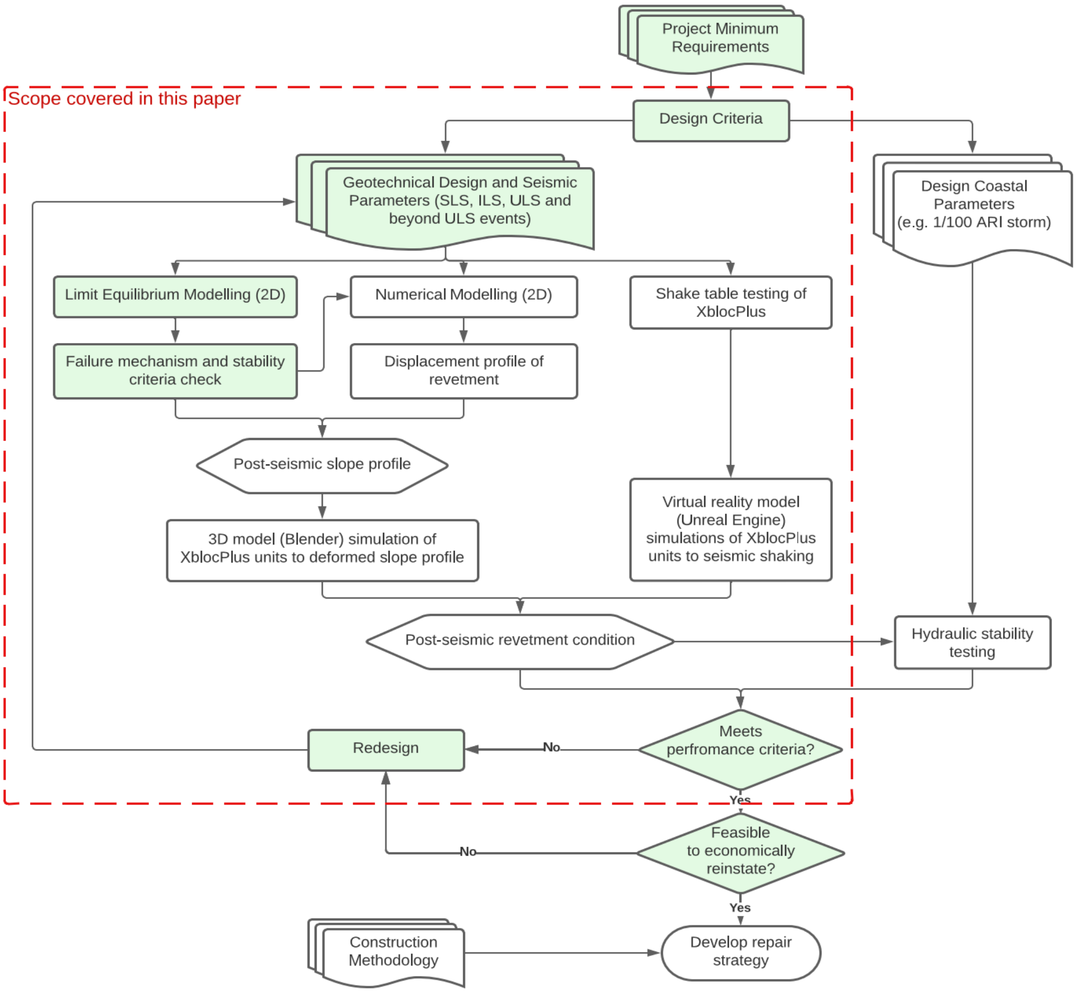


Figure 2. Approach taken to assess seismic and post-seismic hydraulic performance and to develop a repair strategy (highlighted boxes represent analyses that were done as part of compliance with PMR)

The assessments generally indicate that the static geotechnical performance of the revetments meets the design criteria. Slope rotational and translational failure mechanisms were checked, and adequate safety factors were achieved under the different loading scenarios. The performance criteria for SLS design seismic shaking were achieved.

Due to the closeness of the assets to the shoreline, a Newmark sliding block type assessment was carried out to estimate the lateral spreading of the revetments (Ambraseys and Srbulov, 1998; Jibson 2007; Bray et al. 2018). During ULS level shaking (where liquefaction is triggered), the revetments are expected to displace in a relatively controlled manner with limited displacements of no more than 500 mm. Immediately following a ULS earthquake event (i.e. with liquefied soil strengths but no seismic shaking), the revetment is stable, and a flow-type failure is not expected.

However, these approaches consider an overall block-type movement of the revetment and do not allow for the potential for variable movements along the slope profile. The vector movements along the revetment slope (i.e. vertical and horizontal components of displacement) were important to understand the effect of the slope displacement on the XblocPlus units. Hence, numerical modelling of typical revetment cross-sections was also undertaken to understand the displaced profile of the revetment face, refer Section 3.2.2.

3.2.2 Dynamic numerical modelling

Numerical or finite element (FE) modelling of the typical revetment cross-section was carried out using Plaxis 2D (Bentley 2022) to assess the displaced profile of the revetment face. The 2D plane-strain dynamic time history assessment considered conservative ground conditions (i.e. thicker liquefiable layers and the toe of the revetment being founded on the liquefiable materials). This was done intentionally to capture revetment performance under worst-case conditions. The objective of this assessment was to provide a suite of deformed slope profiles to aid with the physical modelling of the XblocPlus revetments for post-seismic coastal modelling and to provide further information on the seismic performance with respect to the PMR.

As discussed in Section 2.3, time history selection and scaling were undertaken to provide a suite of ground motions for the dynamic analysis. Four representative time histories were selected for this assessment, representing the different types of source earthquakes. A total stress analysis was carried out considering scenarios with and without liquefaction. This gave a range of displacements for the selected time histories, with displacements for horizontal or translational movement (X) and vertical displacement or settlement (Y).

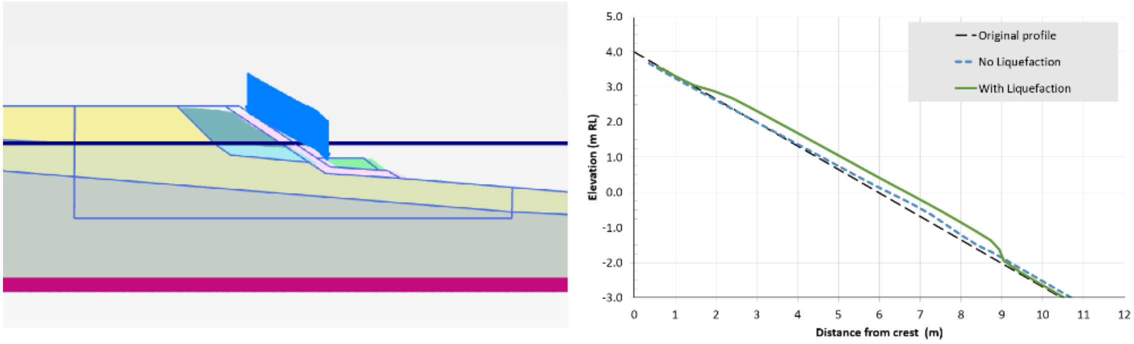


Figure 3. Sample deformed profile and displaced slope profile plots from numerical modelling

From the results, revetments on top of deposits that may liquefy during a ULS shaking were observed to displace preferentially along a surface that passes over the top of the toe buttress. At the maximum displacement location, the XblocPlus units were observed to be pushed seaward by rolling over the base unit buttressed by the toe armour layer. Maximum lateral displacements of about 800 mm were assessed, with the overall displacements being around 650 mm. Figure 3 below shows a sample of the deformed profile and a plot of the displaced profile from the numerical modelling. This is a likely displacement mechanism of the revetment, and corroborates one of the displacement mechanisms observed from the limit equilibrium.

3.3 3D Blender Simulation

One of the numerical analyses' drawbacks was modelling the XblocPlus units. As discussed in Section 3.2, these were modelled as surcharge loading only (without considering the shear strength contribution of the interlock of these units). The numerical modelling was also not suited to model the concrete blocks as discrete elements. Therefore, the ground deformation profile assessed in the numerical modelling was used in a 3D simulation and applied over the earthquake's duration to check the slope displacement effect on the concrete units. i.e. pseudo-dynamic loading where only the X and Y displacements surfaces were modelled.

The Blender 3D modelling package was used for this purpose. A model was developed with XblocPlus units placed over a single layer of cuboid secondary armour, and a toe block was included to represent the toe armour rock. Unit mass and gravity were set to prototype (real-world) values. The secondary armour was placed against a back-slope profile made up of partitioned surfaces capable of being moved by assigned vectors. The secondary armour reduces the response of the XblocPlus units compared to when placed directly on the slope. However, it is likely still conservative compared to the proposed double layer of irregular secondary rock armour that would deform and cushion the response to a higher degree. Based on the numerical modelling results (refer to Section 3.2.2), the back slope was shifted by the magnitude and direction of the slope displacements (shown in Figure 3).

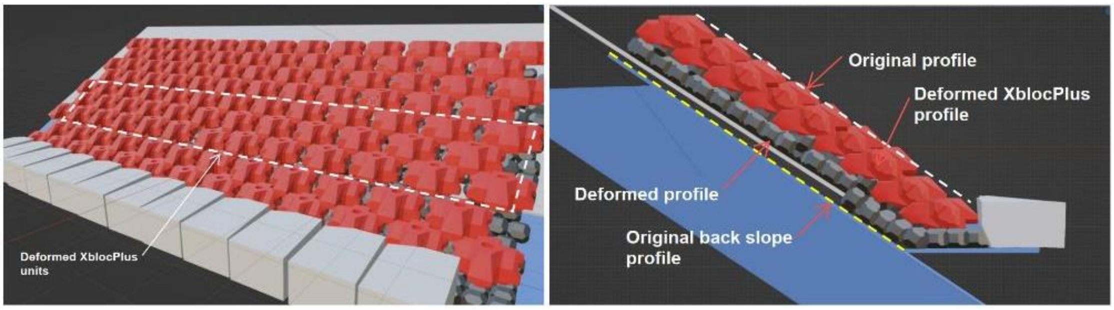


Figure 4. Blender outputs showing XblocPlus response to profile deformation in 3D and 2D; comparing original and post-event or deformed slope conditions

Results (Figure 4) show that where the slope was moved, the two lowest XblocPlus units remained locked together. At the location of the maximum horizontal slope deformation (roughly at the 3rd row), the XblocPlus units were pushed over the lower blocks in places, and the interlock between these units is no longer intact. Above this location, the blocks generally remained interlocked. The observed mechanism is a reasonable behaviour of the revetments, where the differential movement of the slope results in the blocks being displaced out at a location with a high load and no toe buttress. Such a mechanism results in a point of weakness on the slope, though not a complete slope failure. This weakness could, however, be vulnerable to storm events or future seismic events if not repaired.

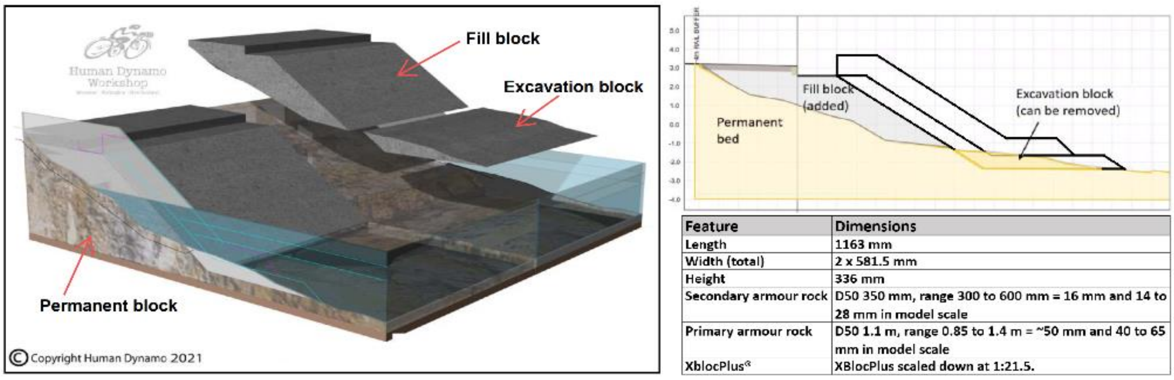
3.4 Shake table testing

A 1:21.5 scale model of the proposed XblocPlus revetment was initially developed for coastal modelling. The model was then utilised to understand the response of the XblocPlus units to seismic shaking (refer to Figure 5). The model features a ‘permanent bed’ representative of the existing bathymetry, a ‘fill block’ for the armour layer to be placed on, and an ‘excavation block’ to place the revetment toe. The model was tested using two 1 g shake tables, one capable of horizontal shaking and another for vertical. The shake tables consisted of a stiff, 2.5 m × 2.5 m square platen that moved the scale model in one direction at a time, i.e. perpendicular or parallel using the horizontal shake table and in the vertical direction using the vertical shake table (refer to Figure 6).

Two earthquakes were simulated based on historical records that were scaled down using Froude’s scaling laws (Iai 1989). Time was scaled by $(1/L^{0.5})$, where L is the model scale, while the acceleration magnitude has remained unscaled (a factor of 1.0). Each acceleration time history record was filtered with a corner frequency of 20 Hz to be used on the shake table, which meant that removing these high frequencies resulted in a general reduction in the peak acceleration values of the records. However, an inspection of the resulting velocity and displacement time histories showed that these differences were negligible. The time series were sampled at a rate of 100 Hz on the shake table, and a scaled and filtered sample response spectra is shown in Figure 6. The simulated earthquakes were then scaled up to simulate different return periods, with the scaling factors indicated in

Table 3.

Several early tests were run on the shake table to check which model arrangement and configuration best represented the actual conditions of the revetments. These early models were also cross-checked versus virtual reality models (discussed in Section 3.5) to verify the model configuration. As an outcome of this cross-check, the most reasonable configuration was to fix the secondary armour to the slope and, therefore, only get the effect of the roughness without this layer displacing. This was achieved using plasticine rolled out across the slope with a single layer of secondary armour pressed into it. Crest rock was placed around the transitions and the crest rock to interlock the units without the interference of the acrylic side walls.



Feature	Dimensions
Length	1163 mm
Width (total)	2 x 581.5 mm
Height	336 mm
Secondary armour rock	D50 350 mm, range 300 to 600 mm = 16 mm and 14 to 28 mm in model scale
Primary armour rock	D50 1.1 m, range 0.85 to 1.4 m = ~50 mm and 40 to 65 mm in model scale
XblocPlus®	XBlocPlus scaled down at 1:21.5.

Figure 5. Scale model isometric view (designed by Human Dynamo), components and properties

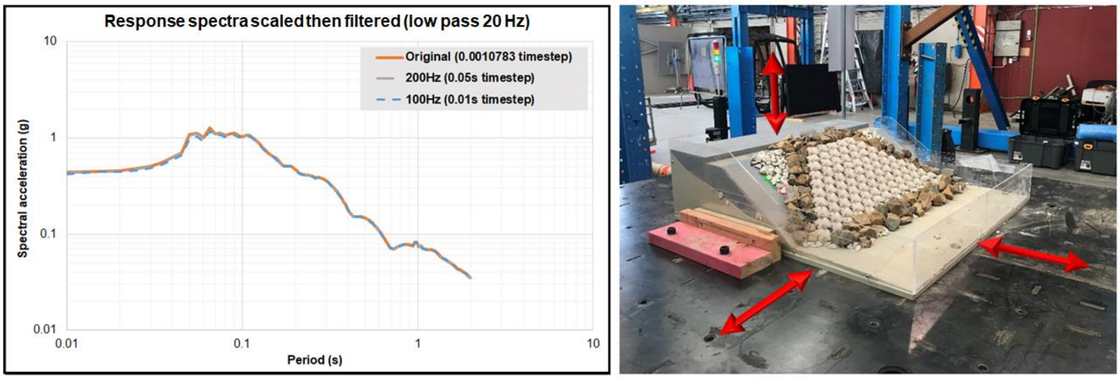


Figure 6. Scaled and filtered response spectra (for a 500-year return period), with typical model set-up prior to a test and showing 1D shake table directions of the test

Virtual reality models

A limitation of the shake table testing is that shaking is unidirectional. A virtual reality simulation software, Unreal Engine (Epic Games 2023), has been used to simulate shaking in three dimensions simultaneously. A model was developed with XblocPlus units placed on top of a single layer of cuboids representing the ‘secondary armour’ with a partial toe restraint to represent the toe armour rock. Unit mass and gravity were set to prototype (real-world) values. Each direction was simulated for the same earthquake sequence described in Section 3.4. The behaviour was calibrated by adjusting friction and the toe restraint to limit sliding while allowing enough movement at the toe to limit the extent to which XblocPlus units in the second and third rows rode up over the lower units.

Table 3 below summarises the observation of the different shake table tests. For this configuration, the design seismic shaking corresponding to different return periods was tested on the shake table. Overall, the results showed negligible residual displacement and damage to the XblocPlus units during the ULS event. Larger shaking events showed potential failure mechanisms with movement down the slope (corresponding to 500 mm or more displacement for full scale) occurring at 1,000-year and higher return periods.

However, it should be noted that these results underpredict the likely displacement of the revetments because only unidirectional shaking was applied. However, this approach provided a glimpse of the potential mode of deformation of the revetments beyond ULS events. The results described above also did not include sliding of the secondary armour. During the initial configuration testing, allowing the secondary armour to slide kept the armour layer more intact and connected. It is also to be noted that the main objective of the shake table tests was to calibrate 3D virtual reality model (Section 3.5), where 3D shaking can be simulated.

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Table 3. Observations of 1D shake table testing

Test	Earthquake return period	Photos (after the test)	Comment*
Perpendicular shaking	500 years (ULS) (SF** = 1.00)		No movement was observed.
	1000 years (SF = 1.40)		Approximately 1-3 cm (200-650 mm prototype scale) of slumping down the slope from the crest.
	2500 years (SF = 2.03)		Bulging in the middle of the revetment likely occurs due to the crest rock pushing down on the top XblocPlus units and rotating the units out of place. Units moved down about 5-8 cm (1100-1700 mm prototype scale) from the crest.
Parallel shaking	500 years (ULS) (SF = 1.00)		No movement was observed.
	1000 years (SF = 1.40)		Approximately 2 cm (450 mm prototype scale) slumping down the slope from the crest.

Test	Earthquake return period	Photos (after the test)	Comment*
	2500 years (SF = 2.03)		XblocPlus units rotated inward in places and slumped down about 4 cm (850 mm prototype scale) from the crest; this caused additional units to dislodge, likely due to being moved into an irregular position in the fixed secondary armour.
Vertical shaking	No movement was observed from the 500-year to a scale factor of 8 in the XblocPlus or the crest rock. Images below are after 500-year, 1000-year and 2500-year return period tests. 		

*Displacements described are: model scale displacements (prototype displacements); **SF = scaling factor

Following this calibration exercise, the full multidirectional (XYZ) displacement time series were applied to the slope. Results for the ULS event (500-year return period) showed localised horizontal displacement of the toe (< 400 mm) and vertical movement of the blocks and secondary armour down the slope (< 200 mm). The XblocPlus units in the second or third row tended to ride over the lowest unit, which was more effectively restrained by the toe. As units rode over the lower units, they often tilted sideways, and the units above would also slightly rotate as their wings or noses lost full or partial contact with the unit below. Above the third row of units, the XblocPlus units generally remained well interlocked while moving down the slope slightly. As the secondary armour rolled down, these blocks also moved down to fill the space the lower units left as they moved out horizontally. This deformation is similar to that observed in response to the profile deformation using the Blender model (Section 3.3). The deformation was not necessarily uniform alongshore but occurred in pockets, as shown by the outlined zones in Figure 7. This suggested that once stresses were released by some units deforming (moving out of the slope), adjacent units could release stress by moving horizontally along the slope.

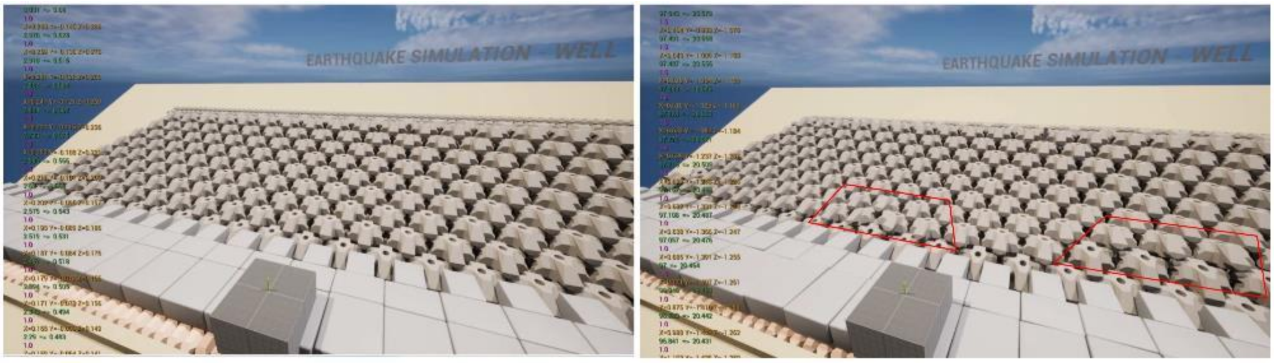

Figure 7. Unreal Engine model showing XblocPlus response to ULS seismic shaking in three dimensions

Larger events (1000 and 2500-year return periods) tended to produce more extreme displacements than the shake table results, such as some blocks being pushed over the lower blocks and toe restraint. On the shake table, the revetment slid down while remaining relatively intact. The difference is mainly attributed to the shake table results being unidirectional. Comparatively, the Unreal Engine simulation, being multidirectional, resulted in a worse performance.

4 SUMMARY AND CONCLUSIONS

As discussed earlier, XblocPlus units provide numerous benefits over the more traditional rock armour, such as reduced footprint requirements and ease of construction, which made it an ideal choice for this Project. Due to the limited uses of this armour solution in high seismic environments and the complexity of the XblocPlus revetment response, a single method or model cannot confidently be used to assess the likely behaviour of the revetment during and following a design seismic event. As a result, a suite of complementary models was used to check the different displacement modes. The following points summarise the outcomes of this study:

- Numerical modelling of the revetment for a ULS event corroborated the limit equilibrium stability modelling and indicated deformation in the form of a bulge near the toe.
- Shake table seismic shaking showed no discernible movements at the ULS acceleration, while the 3D Blender simulation showed some tendency for toe sliding and deformation of the lower XblocPlus rows over the bottom buttressed row. Larger events (beyond ULS) showed either further sliding and decoupling/tilting of the units (shake table) or sliding and riding up of the lower rows (Unreal Engine). Given the lack of calibration data and an inability to accurately model the secondary armour layer, which is likely to have a damping effect on deformations, these results likely form an envelope of the response, with the actual response being a combination of these deformation mechanisms but likely less than observed within the Unreal Engine model.

Based on these outcomes and a post-seismic coastal physical modelling, limited damage of the XblocPlus revetment is expected during a ULS event. A relatively simple and economically feasible procedure can be implemented to inspect and reinstate the structure to a pre-earthquake performance level. In addition to the structure being assessed as meeting the Project objectives and requirements in terms of seismic performance, this design approach provided an in-depth glimpse of how the structure will perform during and post an earthquake event. Knowing the likely displacement mechanism of the revetment also highlighted critical design aspects. Moreover, this design approach enabled a very close inter-discipline collaboration.

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